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DOD/NASA System Impact Analysis (Study 2.1) Final Report

Volume II
Study Results

Prepared by
ADVANCED VEHICLE SYSTEMS DIRECTORATE
Systems Planning Division

15 September 1973

Prepared for OFFICE OF MANNED SPACE FLIGHT
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Washington, D. C.

Contract No. NASW-2472

Systems Engineering Operations

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(Study 2.1) FINAL REPORT

Volume II: Study Results

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FOREWORD

Study 2.1, "DOD/NASA System Impact Analysis," was managed by the Advanced Missions Office of the NASA Office of Manned Space Flight. Mr. Marion Kitchens was the NASA Technical Director of this study. Mr. A. R. Maffei was The Aerospace Corporation Study Manager and was assisted by Mr. D. L. Mumper. Technical support was provided by Messrs. T. J. Lang, B. Moffat, and F. S. Howard.

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1. INTRODUCTION

This final report contains the results of the FY 1973 NASA Study 2.1 performed under contract NASW-2472. This study, entitled "DOD/NASA System Impact Analysis," as originally proposed and negotiated at a level of approximately two manyears, was to consist of ad hoc system analyses as required, a Tug Turnaround Cost Study, and a Tug Refurbishment Logistics Concepts Study. No ad hoc studies were initially specified. In October 1972, direction was given by NASA to conclude the Tug Turnaround Cost Study and to initiate a Space Transportation System (STS) Abort Modes and Effects Study. In January 1973, additional direction was given to update a Space Shuttle Explosive Equivalency Study which had been accomplished under contract NASW-2129 in FY 1971. The Space Shuttle Explosive Equivalency Study was considered an ad hoc study but was covered by additional funding from the NASA Space Shuttle Program Office. The STS Abort Modes and Effects Study was retained as a replacement for the terminated Tug Turnaround Cost Study. The Tug Refurbishment Logistics Concepts Study was never initiated because the manpower allocated to Study 2.1 was expended, with NASA concurrence, in expediting the completion (to 29 November 1972 from March 1973) of the Tug Turnaround Cost Study and in performing the STS Abort Modes and Effects Study. Results of the Tug Turnaround and STS Abort Studies are contained herein while the results of the Explosive Equivalency Study are reported under separate cover.

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2. SUMMARY AND CONCLUSIONS

A. TUG TURNAROUND COST STUDY

During the FY 1972 Tug Refurbishment Cost Study of contract NASW-2301, it was recognized that maintenance and refurbishment represented only a portion of the total ground turnaround costs. The results noted herein utilized the FY 1972 Tug maintenance and refurbishment costs augmented by an analysis of the additional direct and indirect operational costs required to support the ground turnaround cycle of a Tug. In the conduct of the study and in keeping with the Statement of Work, all operational cost elements were assessed for the purpose of understanding Tug turnaround costs within the context of overall Tug operations costs.

To realistically assess the operational costs as a function of the maturity of the system, two time frames of reference were defined: an Initial Operational Capability (IOC) consisting of approximately 20 flights, and a full Operational Capability (OC) following IOC for the remainder of the 12-year mission model. These definitions were utilized in the predecessor Tug Refurbishment Cost Study and were therefore carried into this study. Another carryover of significance was the use of a "dedicated" Tug ground crew of 52 men for IOC and 37 men for OC. These crew sizes were determined in the refurbishment study by analyzing the necessary operations and skill mix required for maintenance and refurbishment. A review of the crew mix for this Tug Turnaround Cost Study revealed that the previously determined crews were sufficient to perform all ground operations. As a result, the "dedicated" Tug crew concept was also adopted for this study as opposed to a manpower pool.

As the definition of Tug turnaround cost can vary, i.e., with or without indirect costs, launch costs, etc., the following overall conclusions

are presented which combine the Tug turnaround-related operations costs in various ways.

1. The total direct costs of an average[1] Tug turnaround, i.e., landing-to-launch, are $519K and $342K for the IOC and OC phases of the flight program, respectively.
2. The total direct operational costs for Tug missions, i.e., launch-to-launch including flight operations, are $665K and $386K for IOC and OC, respectively.
3. The total direct and indirect operational costs for Tug missions, i.e., launch-to-launch including flight operations, are $1,020K and $687K for IOC and OC, respectively.
4. A dedicated Tug ground crew at KSC of 37 men of appropriate skills is sufficient to perform all Tug-related ground operations for the maximum expected launch rate of two per month (OC).
5. The necessity for a similar 37 man crew at WTR combined with its significantly lower Tug launch rate of one every two months (6 per year) could result in significantly higher actual costs per flight at WTR.
6. Government (NASA/DOD, etc.) and non-government user costs may differ significantly due to government policy on the apportionment of many indirect costs to the non-government user. It is recommended that this be pursued in any subsequent effort.

B. STS ABORT MODES AND EFFECTS STUDY

The overall objective of this study was to assess the major effects and impacts of abort on the flight and ground elements of the STS, viz., the Orbiter, Tug, Payload, Ground Support, and Flight Support including Facilities and Equipments. Significant failure modes of the flight elements

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1 The average turnaround costs reported herein combine KSC and WTR operational costs and launch rates.

that could result in a mission abort were identified. These abort-producing failure modes were then related to impacts on the STS elements. The main emphasis of this study was on the identification of Tug-related abort effects and impacts, i.e., those that are caused by the Tug and those that affect the Tug. The performance capability of the Tug vehicle with either degraded main engine thrust or reaction control system thrust was analyzed as a special emphasis task. Also, a cursory analysis was made to assess the on-board data management system requirements for performing all Tug-related abort decisions and operations on board the Tug vehicle.

1. APPROACH

Orbiter vehicle definition used for this assessment was obtained from information presented by North American Rockwell in their November 1972 Space Shuttle System Summary and Program Requirements Review Briefings. The Tug vehicle definition was obtained from the NASA MSFC June 26, 1972, "Baseline Tug Definition Document." Since the payloads to be put into orbit by the STS are many and diverse, representative systems/subsystems were considered; however, no particular baseline design was assumed. The mission used for this assessment was a geosynchronous payload replacement mission.

The approach used to define the effects and impacts of aborts on the elements of the STS was first to define abort regimes for all phases of the baseline synchronous equatorial payload replacement mission. Gross effects of assumed abort-producing failures in each flight element for each abort regime were defined. Next, the actual failure or failure modes were identified and then related to impacts on the STS elements. Because of the state of the design of the Orbiter and Tug vehicles and the many diversified payloads that are planned to be orbited by the STS, a detailed analysis of all the possible failure modes of these STS elements was not attempted. Therefore, the failure analysis was limited to a gross assessment of the possible-failure modes and hazards.

During the conduct of the abort effects assessment, it was recognized that the Tug main propulsion system represented a significant single point failure mode. Therefore, a special emphasis task was conducted to analyze the mission performance capability of the Tug at degraded thrust levels. Both intact (with payload) and jettisoned payload aborts were analyzed. A six degree of freedom flight simulation computer program was utilized for this analysis.

2. RESULTS

a. An abort during the Shuttle ascent phase of the mission impacts both the Orbiter and Tug design. These vehicles must be designed to land with a full load of Tug propellants or provide for rapid dumping.

b. A failure in the baseline Tug electrical power supply (single fuel cell) could result in the loss of the Tug and its payload.

c. Orbiter aborts after Tug deployment could result in the requirement to extend the quiescent on-orbit Tug capability.

d. A Tug failure could result in payload abandonment in an off-nominal orbit.

e. Altered flow of flight elements through the ground turnaround cycle due to a mission abort may tax the capabilities of the ground facilities.

f. Partial mission completion is possible in the event of a Tug main engine failure by using either Tug main engine idle mode or reaction control system thrust. The reaction control system requires access to the main propellants in order to provide the required ΔV. The baseline Tug design used for this assessment does not have this feature.

g. The results of the cursory autonomous abort assessment indicate that a computer size of 65K words would be adequate for all Tug functions including autonomous abort.

C. SUGGESTED ADDITIONAL EFFORT

1. TUG TURNAROUND COSTS

The Tug Turnaround Cost Study, being an extension of the previously completed Tug Refurbishment Cost Study, was limited to a single Tug configuration, i.e., high performance, cryogenic propellant, reusable Tug. It

is recommended that the operational costs of the following Tug candidate concepts be studied to be compatible with alternate Tug concepts being analyzed by the NASA and DOD.

a. Phased developed cryogenic propellant Tugs
b. Storable propellant reusable Tug
c. Modified existing upper stages.

As a result of this study, several cost-driver areas were identified which warrant further in-depth study irrespective of the Tug concept selected. These areas are discussed in the subsequent paragraphs.

a. Indirect Operations Costs

Indirect Tug Operations Costs include Facility and Equipment Maintenance, Replacement Training, Engineering Support, and Program Integration and Management. Of the operations costs, the cost-driver areas of Tug Equipment Maintenance and Engineering Support accounted for almost 40 percent of the total direct and indirect per flight operations costs. The recurring nature of the costs, which are somewhat independent of launch rate, necessitated an assumption of average launch rate to establish per flight costs. It is recommended that a comprehensive study be conducted regarding these indirect cost-driver areas and the applicability of these costs as user or institutional base costs.

b. Tug Refurbishment Logistics Concepts

As noted in the Introduction, this study was originally planned to be accomplished within this contract following the accomplishment of the Tug Turnaround Cost Study. It was not accomplished due to the priority of other studies; however, it is recommended that it be considered in any subsequent effort. Major areas that should be addressed include the logistic relationships between NASA, DOD, and the various Tug contractors, i.e., vehicle, facilities, equipment, etc. Additionally, the effect of the Shuttle equipment and personnel at the same launch facilities should be addressed. Specifically,

the study is needed to assess various approaches to Tug logistics. Various concepts concerning the approach to vehicle maintenance should be identified. The question of who will perform the maintenance and the impact on the total program should be addressed, e.g., private contractor versus the use of a government organization to perform vehicle maintenance. The impact on the funding level and the level of support required at the manufacturer for various approaches to spares support should be identified, i.e., all spares purchased at the beginning of the program or purchased over a longer time span.

2. STS ABORT MODES AND EFFECTS

The impacts on the various elements of an abort producing failure in one of the STS flight elements represent design features and requirements that may or may not be practical or desirable to implement. The impact on the Orbiter of an abort during the ascent phase of the Shuttle flight is dependent on whether or not there is enough time to dump the Tug propellants. A trade study would be required to determine whether the Orbiter should provide for propellant dump, design for the added payload weight, or accept a reduction in the structure safety factors. The impacts on the Tug vehicle would also have to be considered. At the time of the writing of this report, the Shuttle abort capability was in the process of being revised, i.e., the capability for thrust terminating the solid rocket motors was deleted. This should result in an increase in the minimum time for propellant dump. Until the Shuttle abort capabilities are adequately defined, no definite design impacts can be determined.

In the event of an Orbiter failure which necessitates the early return of the Orbiter prior to Tug retrieval, the Tug may be required to remain on orbit longer than anticipated. If the failure occurred just prior to Tug retrieval and the Orbiter required two weeks to be refurbished and processed through the ground turnaround cycle, then the Tug would have to stay on orbit an additional two weeks if no other Orbiter were available. The baseline Tug has approximately seven days on-orbit capability. Hence, some of the Tug

systems, e.g., electrical power and propellant supply for attitude control, would require additional capability to survive the added time on orbit. The degree to which this added capability should be incorporated and the resultant impact on the Tug design should be the subject of a study.

The main impact on the payload derived from the abort assessment is the result of a Tug failure which requires the Tug to jettison the payload in an off-nominal orbit. Hence, the payload would have to survive in this orbit until retrieved by a subsequent Tug flight. The impact on the payload is a function of the difference between the design orbit and the off-nominal orbit, i.e., if the payload were designed to operate at synchronous altitude and instead the payload were deployed in a low earth orbit the difference in the heat input from the earth's albedo and the sun may result in damage to the payload. Whether or not the payload should be designed to account for the possibility of an off-nominal orbit insertion should be the subject of a trade study for each individual payload which would address the probability of this occurrence and the impact on the payload design.

The cursory analysis of data management system requirements for Tug autonomous abort capability has permitted a general definition of the scope of the problem and the development of some broad guidelines for further steps in the systems analysis/development process. The greatest single uncertainty factor in determining the overall feasibility of incorporating an autonomous abort capability in the Tug data management system is the question as to the degree to which the functions now performed by human beings in the areas of fault diagnosis, mission plan generation, and mission plan verification should be automated. This question should be addressed in any follow-on effort.

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3. TUG TURNAROUND COST STUDY

A. BACKGROUND

During FY 1972 a Tug Refurbishment Cost Estimate was developed for a reusable cryogenic propellant Tug. This effort, conducted as part of Study 2.4 of contract NASW-2301, consisted of an in-depth analysis of the scheduled and unscheduled refurbishment costs of a representative Space Tug (Ref. 1 and 2).

The Tug Turnaround Cost Study reported herein is the extension of the Tug Refurbishment Study to include other direct and indirect ground operations costs that are incurred in the turnaround cycle. Additionally, all other remaining operations cost elements are assessed to present a complete picture of the total expected operations costs of the Space Tug.

B. SCOPE

The Tug Turnaround Cost Study was intended to be a bottoms-up cost estimate of all Tug operational cost elements, with results available approximately six months after contract NASW-2472 go-ahead. This study was accelerated to completion in two and one-half months because of the higher priority of the Abort Modes and Effects Study. As a result, the study was terminated at this interim milestone, producing operations costs which were derived by a mixture of bottoms-up and historically based parametric costs, i.e., cost estimating relationships (CERs).

C. STUDY APPROACH AND GROUND RULES

1. STUDY APPROACH

As previously noted, the major objective of the study was to develop a Tug turnaround cost estimate; however, it was also necessary to retain

the perspective of the Tug turnaround costs within the context of overall Tug operations costs. As a result, each of the following cost elements was addressed.

a. Launch Operations
b. Recovery Operations
c. Command and Control
d. Replacement Training
e. Facility and Equipment Maintenance
f. Vehicle Maintenance
g. Engineering Support
h. Program Integration and Management
i. Follow-On Spares
j. Propellants and Gases
k. Range/Base Support.

These elements constitute the total Tug operations costs and are identical in definition and content to the cost estimating relationships (CERs) developed in a joint NASA/DOD funded Space Transportation System (STS) Cost Methodology Study (Ref. 3). It was not the objective of this study to update or in any way modify the CERs; their definition and content were retained only for consistency and traceability.

A significant portion of the turnaround and pre-flight costs for a reusable Tug is the refurbishment cost. As noted in Section 3.A, this was the subject of an in-depth study conducted for NASA Headquarters in FY 1972. Since this Tug Turnaround Cost Study was an extension of the Tug Refurbishment Study, the results of the refurbishment study were used directly as cost inputs in the areas of vehicle maintenance and follow-on spares.

Section 3.D of this report defines and assesses the cost of each of the aforementioned operations cost elements, i.e., launch operations,

recovery operations, etc. Additionally, the cost elements are combined to present direct and indirect Tug turnaround costs and Tug pre-flight operations costs.

2. GROUND RULES/GUIDELINES

The following is a listing of the overall ground rules/guidelines used in the conduct of this study. Ground rules/guidelines unique to a particular operational cost element are identified as part of the assessment of that element in Section 3. D.

a. The baseline Tug is that which resulted from the FY 1972 Tug Refurbishment Cost Study (Ref. 1).

b. The combined NASA/DOD mission model contains 304 Tug flights over a 12-year period with an approximate launch rate of two per month from KSC and one every two months from VAFB.

c. The definition for each cost element analyzed is as stated in Section 3. D and Ref. 3.

d. NASA is assumed to be the host at KSC and DOD is assumed to be the host at VAFB.

e. Tug maintenance facilities will exist at KSC and VAFB.

f. Normal and contingency operations are considered in Tug turnaround operations.

g. Separate estimates for IOC (first 20 flights) and full operational capability (OC) are presented where appropriate.

h. Cost estimates are in 1971 dollars (multiply by 1.07 to obtain 1973 dollars).

D. TUG OPERATIONS PHASE COST ESTIMATES

This section contains the analyses and cost estimates of the elements that make up the total costs of Tug operations. The cost elements are identical in number and definition to the cost estimating relationships (CERs) of Ref. 3. In most instances a bottoms-up cost estimate was generated for the cost elements of this Tug Turnaround Study independent of the methodology

utilized for the CERs. As a point of reference, however, Appendix A contains a summary of the applicable Tug operations CERs that could be used to determine in a top-down manner the Tug operational phase costs.

It is anticipated that after a few Tug test flights there will be a group of approximately 20 Tug flights that will be termed initial operational capability (IOC). This in turn will be followed by full operational capability (OC) for the remainder of the program. It is expected that the operations costs will differ between the IOC and OC phases of the Tug program. This differentiation was recognized in the predecessor Tug Refurbishment Cost Study and is carried into the present study. Section 3.D.12 summarizes the effects of these IOC and OC cost differences and also separates the costs into "direct, indirect, and institutional (support)" costs. Finally the costs are arranged to determine Tug turnaround and Tug operational costs for the IOC and OC phases.

1. LAUNCH OPERATIONS

a. Definition

Refers to the direct costs of launching the Tug elements. Includes final pre-flight assembly and checkout, actual countdown, and launch operations.

b. Cost Analysis

The functional flow diagram for this phase of operations is shown in Figure 3-1. Figure 3-2 shows the total STS turnaround timeline, including the launch operation's timing allowances. The support requirements for each block function were determined including personnel requirements. The buildup of manning and manhours was then derived by applying the defined Tug task durations from the timeline to the derived personnel requirements. Where the timeline did not provide task durations, reasonable assumptions were made. Table 3-1 presents the buildup and provides crew composition and commitment data as well as manhour requirements for the OC flight phase. Ref. 1 provided the basis for the estimates made in this area. To account for initial learning, the IOC manpower estimates were obtained by multiplying the OC estimates by a factor of 1.5.

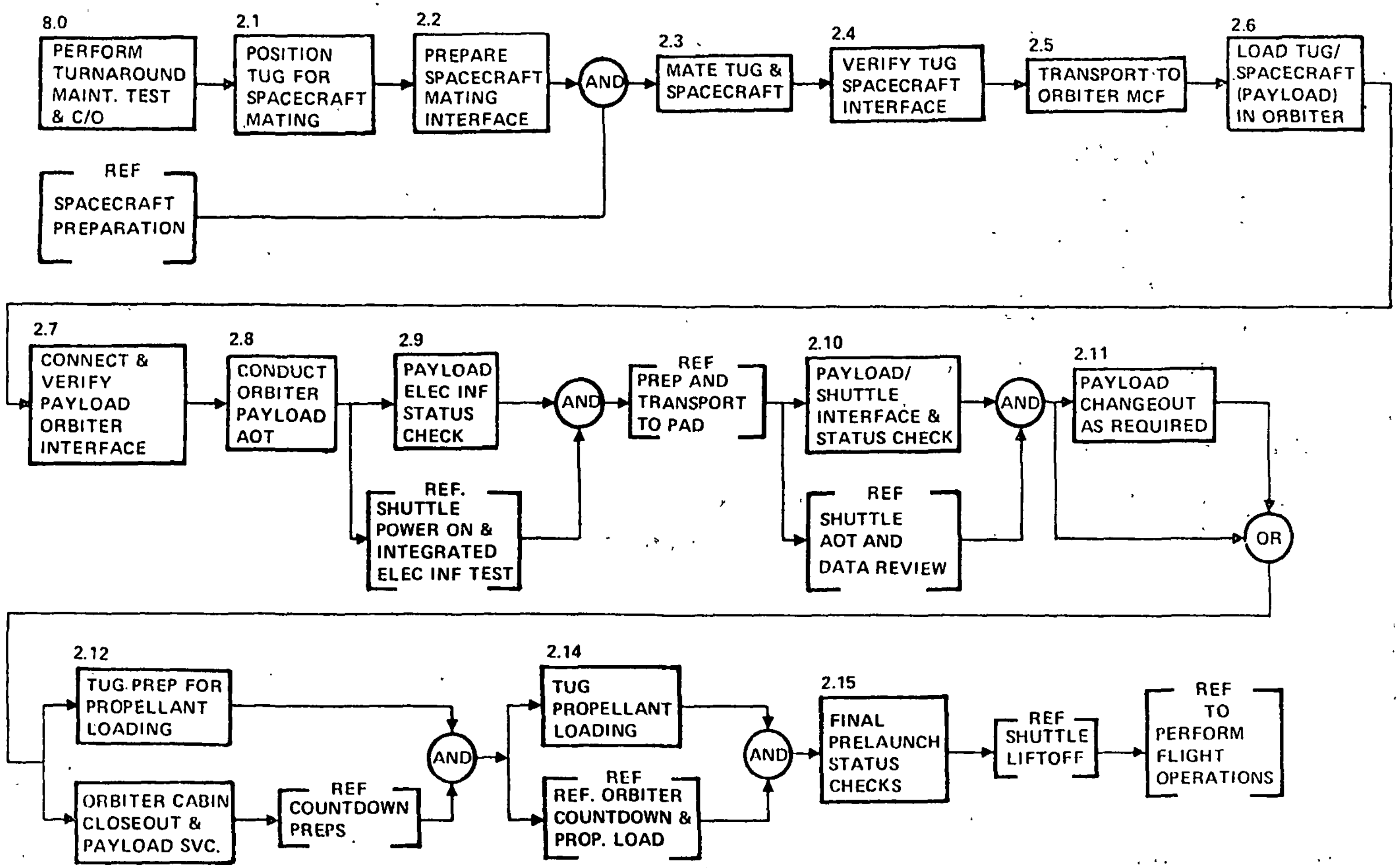

Figure 3-1. Tug Pre-Launch and Launch Operations

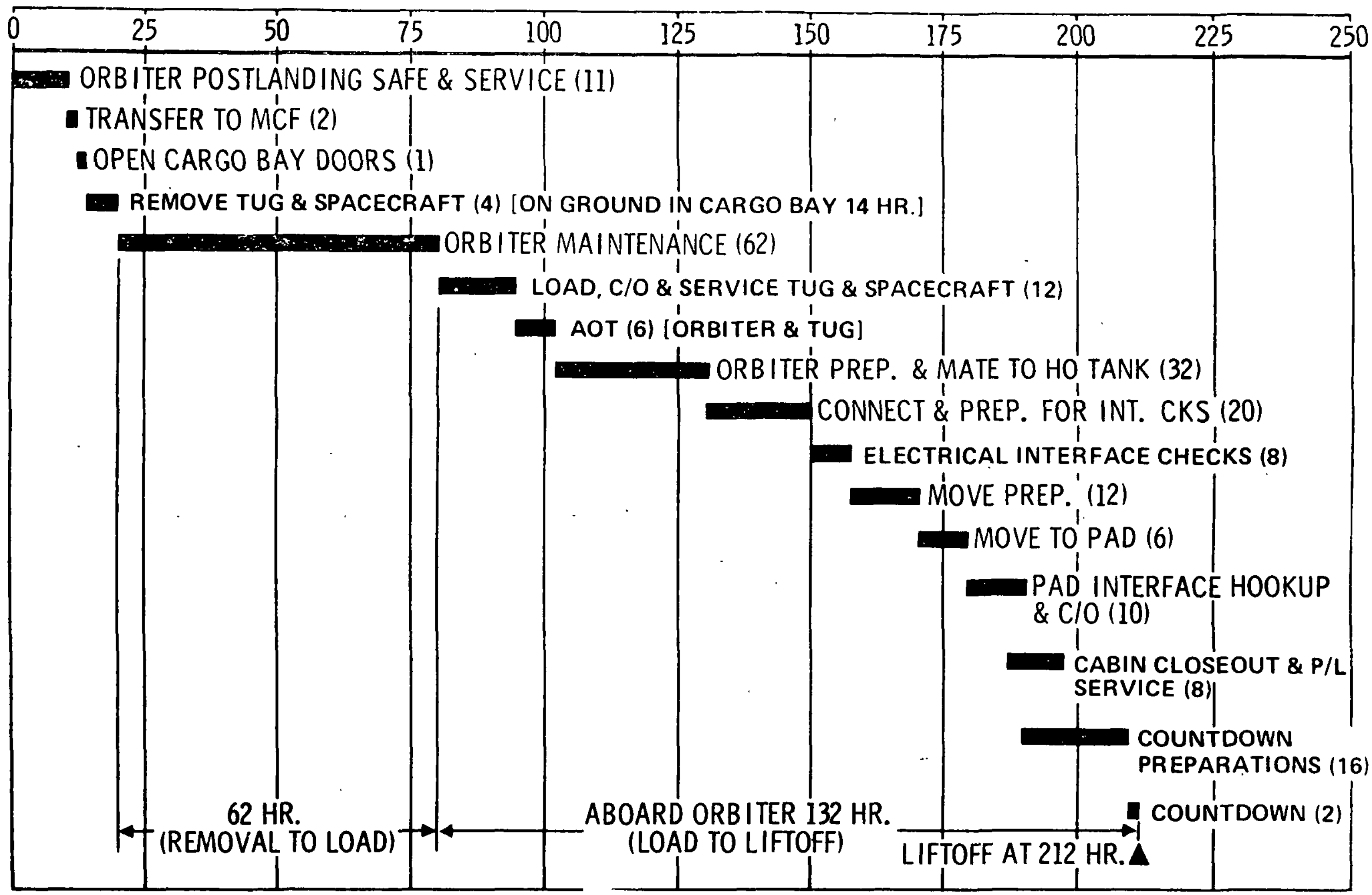

Figure 3-2. STS Processing Time Constraints Based Upon Shuttle Timelines

Table 3-1. Launch Operations Manning Requirements (OC)

Task	Personnel	Duration (hr)	Man-hours
Transport, Prepare Tug and Spacecraft for Integration	Tractor Driver - 1 Escort Vehicle Drivers - 2 Ground Handling - 4 Technician	4	28
Integrate Tug & Spacecraft (Mechanical Only)	Ground Handling - 4 Technician	4	16
Transport, Prepare Tug/ Spacecraft for Orbiter Load	Tractor Driver - 1 Escort Vehicle Driver - 2 Ground Handling - 4 Technician	6	42
Load/Integrate Tug/ Spacecraft in Orbiter	Ground Handling - 4 Technician Tug Propulsion - 2 Technician Tug Avionics/Elect. - 2 Technician LPS Operator - 1	18	162
Preparation for Tug Loading Propellant	Tug PLS[1] Technician - 1 LPS/PLS Operator - 1	1	2
Tug Propellant Loading	Tug PLS Technician - 2	1.5	4.5
Pre-Launch Status Checks	Tug Avionics/Elect. - 2 Technician LPS Operator - 1	0.5	1.5
		TOTAL:	256

Cost @ $17/hour = $4,352

[1] Propellant Loading System

2. RECOVERY OPERATIONS

a. Definition

Includes the cost of performing recovery operations, propellant purging, vehicle deactivation, and servicing. Assumes that Tug elements return within the Shuttle Orbiter.

b. Cost Analysis

Figure 3-3 is the functional flow diagram for this phase of Tug turnaround operations. As indicated in Figure 3-2, the time period covering the activity consists of 14 hours through Tug/payload removal. To this must be added allowances for transportation and payload demate before the Tug is ready for the maintenance phase of operations. Table 3-2 presents the assessment of the effort involved for the OC flight phase. In some cases recognition was given to an assignment for the overall time span of the activity and not just the time required for a specific sub-task (e.g., removal of the flight data recorder tapes). A 1.5 factor was used to convert OC estimates to IOC estimates.

3. COMMAND AND CONTROL

a. Definition

Includes costs associated with ground command, control, and tracking from vehicle launch through mission completion and return. Includes such functions as flight control, telemetry, communications, data processing, and data analysis.

b. Cost Analysis

The baseline Tug used in this overall study is by definition autonomous which, in the context of command and control, infers an "airline" rather than "space flight" type of operation. The result is a significant reduction in the number of personnel required to support Tug flight operations. Those that are retained are used primarily to support the "executive override"

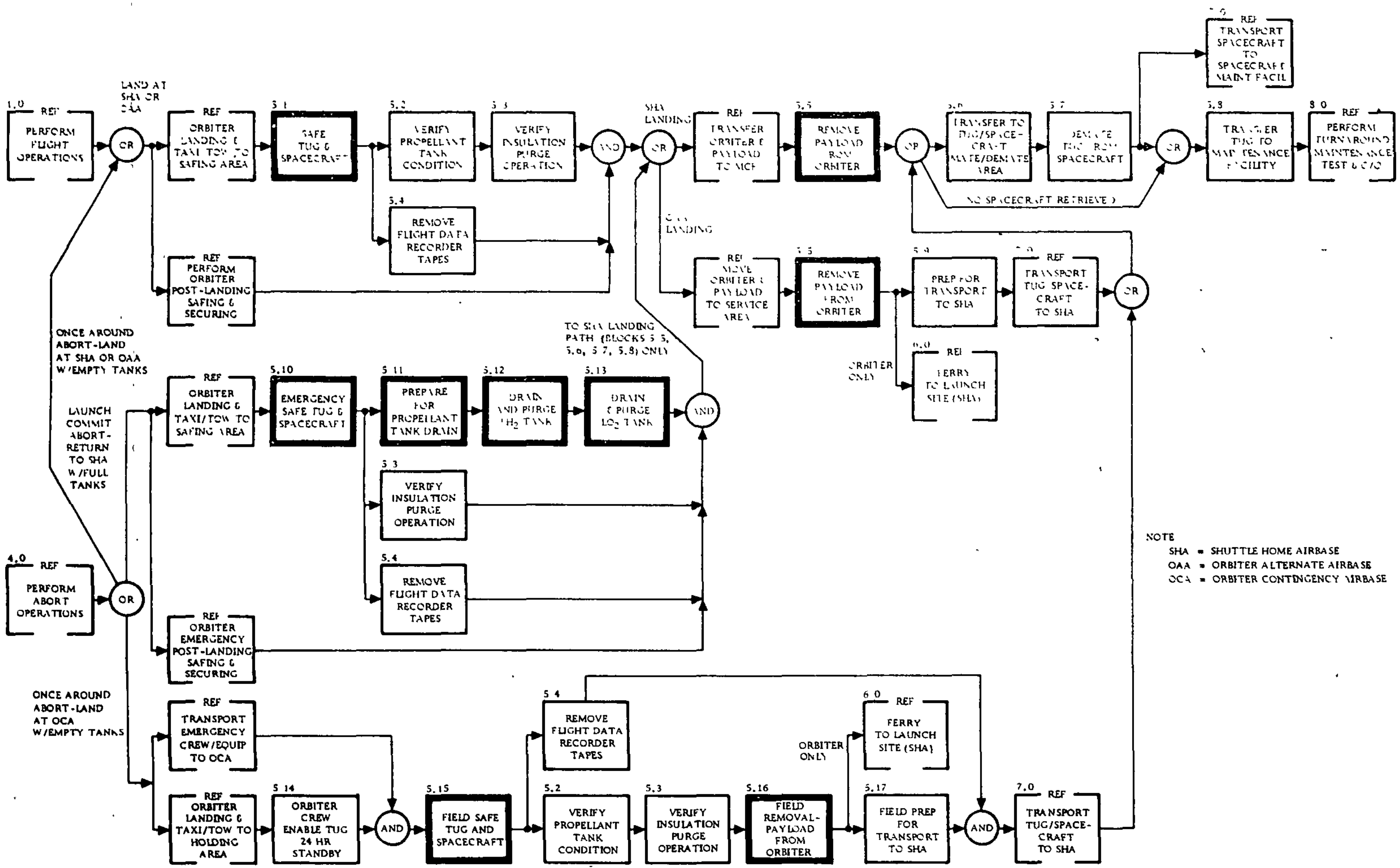

Figure 3-3. Tug Post-Landing Operations

Table 3-2. Recovery Operations Manning Requirements (OC)

Task	Personnel	Duration (hr)	Manhours
Safe Tug Systems	Tug Propulsion Technician - 1	11	11
Remove Flight Data Recorder Tapes	Tug Avionics Technician - 1	11	11
Remove Tug Spacecraft from Orbiter	Tug Ground Handling Technician - 4 Tug Propulsion Technician - 1 Tug Avionics Technician - 1	4	24
Move Tug/Spacecraft to Demate Facility, Prepare for Demate	Tug Ground Handling Technician - 4 Tow Tractor Driver - 1 Escort Vehicle Driver - 2	4	28
Demate Tug and Spacecraft	Tug Ground Handling Technician - 4	4	16
Move Tug to Maintenance Facility	Tug Ground Handling Technician - 4 Tow Tractor Operator - 1 Escort Vehicle Driver - 2	2	14
		TOTAL:	104

Cost @ $17/hour = $1768

function which has been retained as a baseline requirement. Flight operations are conducted from the Johnson Space Center (JSC) for NASA flights and from the Air Force Satellite Control Facility (AFSCF) for Department of Defense (DOD) flights. As noted in the ground rules, NASA is the host at Kennedy Space Center (KSC) and DOD is the host at Vandenberg Air Force Base (VAFB); however, each agency will control its Tug flights from JSC and AFSCF independent of the Shuttle/Tug launch location. As a result, the Tug Operations contractor is required to have personnel at both JSC and AFSCF to the extent noted in subsequent paragraphs.

Command and control costs should be divided into direct and indirect cost categories. The direct costs would be those costs directly funded by the Shuttle or Tug program, whereas the indirect costs would consist of the "institutional" operating costs for the AFSCF and NASA Mission Control Center (MCC) including flight support systems. The direct costs would cover personnel provided by the program such as the mission director and subsystem specialists to monitor mission performance.

The indirect institutional costs would include manning of remote tracking sites and the mission control facility, computer operation for ephemeris determination and formatting of telemetry data, encoding and transmitting commands, and receipt of telemetered data. For the Shuttle traffic, two mission control rooms are required at the AFSCF and a similar number is probably required for NASA. These control center rooms would support on-orbit operations as well as launch operations during which they would ascertain whether the communications system is operating properly so that they can effect commands and receive telemetry.

(1) Direct Costs

Direct costs include personnel provided by the Tug program to the MCC such as the mission director and subsystem specialists who monitor mission performance.

The DOD flight rate is approximately eight Tug flights per year. This could be handled with two full-time crews at the AFSCF with support from sustaining engineering on an "as needed" basis. The crew size was estimated to be 10 people/shift for a total of 20 people in support of early IOC flight and three people/shift for a total of six people for the OC flights.

The NASA flight rate is almost double the DOD Tug rate and would justify manning the equivalent of one center full time (three people per shift) and the second center at half-time or approximately 18 total (includes allowance for weekends, vacations, etc.) for the OC flight phases. For IOC, the total crew size was estimated to be 60 people.

(2) Indirect Costs

Indirect costs include operation of the flight control network and mission control facility. This covers remote sites, mission control, computer operation for determining ephemeris and formatting data, encoding and transmitting commands, and the receipt of telemetered data. This cost will normally be requested by the AFSCF or NASA MSFN system in their budget requests for the Shuttle and Tug support.

These costs are based on the number of control rooms required. For DOD Shuttle operations, two rooms are required which represent one-sixth of the AFSCF capability for the Shuttle. This cost would exist with or without the Tug. However, it is assumed that one out of three flights at WTR includes a Tug, and therefore one-third of the Shuttle costs are attributed to the Tug. It is further assumed that DOD and NASA support system costs are equal.

Indirect Costs

$$= \text{Network Budget} \begin{pmatrix}\text{Fraction for}\\ \text{Shuttle}\end{pmatrix} \begin{pmatrix}\text{Fraction for}\\ \text{Tug}\end{pmatrix} \begin{pmatrix}\text{No. of}\\ \text{Years}\end{pmatrix} \left(2^{1}\right)$$

$$= 150 \times 10^6 \quad \left(\frac{1}{6}\right) \quad \left(\frac{1}{3}\right) \quad 12 \quad (2)$$

$$= \$200M$$

[1]Assumes NASA MSFN and AFSCF costs are equal.

4. REPLACEMENT TRAINING

a. Definition

Includes the cost of training qualified ground crew personnel to replace those lost by rotation or attrition in order to maintain manning at levels necessary to meet flight and ground operation schedules.

b. Cost Analysis

This cost element was estimated using the 25 percent cost factor developed for Replacement Training CER, Appendix A. The size of the ground crew for the IOC and OC phases of the program is defined in Section 3.D.6, where it is concluded that the crew required for Tug refurbishment is also sufficient to support all other ground operations. For the two launch facilities, KSC and VAFB, a total of 104 and 74 men are required for the IOC and OC phases, respectively. Replacement training costs are therefore 26 and 18.5 man-years per year for the IOC and OC phases, respectively, at a training cost of $17,250 per man.

5. FACILITY AND EQUIPMENT MAINTENANCE

This cost element is further divided into the maintenance of Facilities and the maintenance of the Ground Support Equipment.

a. Launch and Maintenance Facilities Maintenance

(1) Definition

Includes the cost to maintain, preserve, and repair launch and maintenance facilities. Refers to all launch, recovery operations, and maintenance facilities used in the operational program.

(2) Cost Analysis

The CER for facility cost is already based on a bottoms-up approach as shown in the CER equation:

Operational and Maintenance Facility Cost =

$$5.0 \times 10^6 + 45\,(1.6\ \mathrm{NC1} \times \mathrm{AC} + 20{,}000) + 30\,(1.6\ \mathrm{NC1} \times \mathrm{AC})$$

45	=	Cost of construction, $\$/ft^2$ - maintenance
1.6	=	Walk-around area factor
NC1	=	Number of vehicles in maintenance
AC	=	Floor area of each vehicle ($15 \times 35 = 525$ ft)
20,000	=	Other floor space for equipment, etc.
30	=	Cost of construction, $\$/ft^2$ - storage

The 5.0×10^6 figure is for other supporting facilities and installations such as cryogenic supplies, gases, and miscellaneous shops and was derived from detailed costing for individual installations. The cost of the facilities was therefore calculated as follows, assuming four Tugs assigned to KSC (Site 1) and three to VAFB (Site 2).

Facility Cost, KSC

$$= 5.0 \times 10^6 + 45\,(1.6 \times 525 \times 4 + 20{,}000) + 30\,(1.6 \times 525 \times 4)$$
$$= \$6{,}152{,}000$$

Facility Cost, VAFB

$$= 5.0 \times 10^6 + 45\,(1.6 \times 525 \times 3 + 20{,}000) + 30\,(1.6 \times 525 \times 3)$$
$$= \$6{,}089{,}000$$

The facility maintenance cost then results from application of a 5 percent factor for annual maintenance, based on historical data; the cost per flight is a function of the yearly traffic rate, for example, for 24 at KSC, six at VAFB.

Launch Site		Per Year
KSC (24 flights)		\$307,600
VAFB (6 flights)		\$304,450
	Total	\$612,050

b. Ground Support Equipment (GSE) Maintenance

(1) Definition

Includes the cost to maintain, preserve, and repair ground support equipment. Refers to all ground support equipment used in operations program. Includes propellant production plant maintenance.

(2) Cost Analysis

The 5 percent factor for yearly equipment maintenance is considered appropriate for planning purposes, as it is based on historical data. The primary problem is therefore the determination of the cost of the GSE required for each site. The detailed CER for this element is based on relationships to vehicle parameters and is not suitable for a bottoms-up estimate.

Ground support equipment costs have been only briefly examined for the Tug. North American Rockwell in their Space Tug Point Design Study for NASA MSFC developed an estimate of $20M for the GSE on site, but similar estimates are not available from other contractors. It is therefore necessary to refer to relevant current vehicles to get some measure of the GSE cost magnitude for validation of the NAR estimate.

During FY 71, The Aerospace Corporation conducted a study for NASA of space operations as supported by the STS and other candidate launch systems. Research for that study involved the determination of the costs to implement various current vehicle capabilities on existing launch facilities. The following data were obtained relative to the cost of such resources for the noted vehicle stages:

Titan IIIF -	Electrical GSE	$ 19.5M
	Mechanical GSE	$ 4.5M
	Total	$ 24.0M
	Centaur - GSE (some facility mods)	$ 26.0M
	Agena - GSE only	$ 8.0M

These figures provide a range from $8M to $26M and would indicate the reference figure as fairly accurate, particularly as the Tug equates roughly to the Centaur. Qualification is necessary, however, as the referenced totals are for reorders of existing equipment. Some allowance must be made for the RDT&E cost, and a factor of 25 percent was applied to the $20M reference value to produce a Tug support equipment estimate of $25M.

The following summarizes the maintenance costs for support equipment after application of the 5 percent factor:

Launch Site		Per Year
KSC (24 flights)		$1.25M
VAFB (6 flights)		$1.25M
	Total	$2.50M

6. VEHICLE MAINTENANCE

As noted in the Background section, this Tug Turnaround Cost Study is an extension of a previous Tug Refurbishment Cost Study conducted as part of FY 1972 Contract NASW-2301 (References 1, 2). The Tug Refurbishment Study developed in-depth costs for both the manpower and spares required to maintain a Reusable Space Tug. The results of the refurbishment study are directly used in this Vehicle Maintenance section.

a. Vehicle Description

The Tug used for this study was synthesized from data obtained from NASA- and DOD-funded Tug/OOS studies and Aerospace in-house efforts. The vehicle is an integral propulsion stage utilizing liquid hydrogen and liquid oxygen as propellants and is capable of operating either as a fully or a partially autonomous vehicle. Structural features are an integral LH_2 tank (mounted forward), an LO_2 tank (mounted aft), a meteoroid shield, an aft-conical docking and structural support ring, and a new staged combustion main engine. The vehicle is constructed of major modules for ease of maintenance.

b. Cost Analysis

In Ref. 1, the baseline Tug vehicle was divided into 11 major vehicle areas plus testing for which refurbishment costs were generated. Table 3-3 shows the average refurbishment manhours per mission for each of these areas for IOC and OC. The manhours include both scheduled and unscheduled maintenance requirements.

The manhour requirements listed in Table 3-3 assume the existence of a labor pool from which the necessary manpower is obtained on an as-needed basis. Vehicle maintenance then is charged only for the manhours actually expended maintaining the Tug. Ref. 1 indicated that the Tug would require 52 men during IOC and 37 men during OC for Tug maintenance. Hence, for a dedicated Tug maintenance crew concept, vehicle maintenance manpower costs would be based on the yearly cost of a crew size of 52 men and 37 men for IOC and OC, respectively. A review of the skills involved indicated that this dedicated crew could also be used for launch and recovery operations.

7. IN-PLANT ENGINEERING SUPPORT

a. Definition

Includes costs associated with normal product improvement or evolution, characterized by engineering changes and modifications to the Tug vehicles or "modus operandi" of the system. The changes and modifications may occur as a result of user recommendations, or operational experience. This category also includes costs of in-plant engineering liaison support of operational activities. The tasks covered herein generally occur after the first vehicle has entered the operational inventory and continue through the end of the system life cycle. Excluded are costs that pertain to major hardware modifications required to meet new performance specifications.

Table 3-3. Vehicle Maintenance Man-Hours/Mission

	IOC	OC
Basic Structure	32	32
Meteoroid Shield	60	60
Tug-P/L Dock.	35	32
Tug-Shuttle Dock.	26	26
Propel. Tanks	382	279
Interface Panels	18	15
Tank Insulation	250	203
Main Prop.	494	341
Aux. Prop.	587	415
Elect. Power	68	44
Avionics	494	285
Test	1,100	750
Total	3,546	2,482

b. Cost Analysis

Both in-plant engineering support and program integration and management were addressed in a previous study under the title of Sustaining Engineering. The results of the analysis were reported to NASA in Ref. 2, "Analysis of Space Tug Operating Techniques Supplemental Report (Study 2.4)." The data presented in that report were used as the basis for the current estimates. Recognition has also been given to the differing levels of support required for the IOC and OC operational phases. Table 3-4 summarizes the manpower requirements for in-plant engineering support.

8. PROGRAM INTEGRATION AND MANAGEMENT

a. Definition

Refers to the costs associated with the management and unification of the operations phase. All operational activities are coordinated by this function to ensure the successful accomplishment of the mission objectives. Includes planning and scheduling of flights, flight modes, payload-vehicle assignments, etc.

b. Cost Analysis

The estimates for program integration and management were developed in Ref. 2 and are summarized in Table 3-5.

9. FOLLOW-ON SPARES

a. Definition

Includes the costs of spare parts and components produced to replenish initial spare stocks in support of Tug maintenance and overhaul, both scheduled and unscheduled.

b. Cost Analysis

As noted in the Vehicle Maintenance Section (3. D. 6), spares costs associated with maintaining the Tug were developed in a previous Tug Refurbishment Cost Study and are summarized in Table 3-6.

Table 3-4. In-Plant Engineering Support

	In-Plant		KSC		VAFB		NASA Center	
	IOC	OC	IOC	OC	IOC	OC	IOC	OC
Structures/Stress	8	6						
Main Propulsion	4	2						
Auxiliary Propulsion/ Attitude Control	4	2						
Thermal Control	3	2						
Electric Power and Control	3	2						
Communications and Instrumentation	8	6						
Guidance and Navigation	11	10						
Flight Control	2	2						
Data Processing/Analysis	8	6						
Fluid Systems (Hydraulic and Pneumatic)	2	2						
Mechanical Systems (including Docking, Ordnance)	4	3						
Support Systems (Electrical/ Mechanical GSE, Facilities)	7	5						
Reliability/Maintainability	3	3						
Test Engineering	5	4						
General Engineering Support (@ 10%)	10	8						
Technical Liaison/Engineering Representatives			4	3	3	1	4	4

Total IOC = 93 men
Total OC = 71 men

Table 3-5. Program Integration and Management

Functional Category	In-Plant	
	IOC	OC
Mission Planning and Performance (including weights)	6	5
Configuration Control, Procedures Management, Interface Control	6	5
Program Control/ Management	7	6
Logistics Management	6	4

Total IOC = 25 men
Total OC = 20 men

Table 3-6. Follow-On Spares, $K/Mission

	IOC	OC
Basic Structure	-	-
Meteoroid Shield	10	10
Tug-P/L Dock.	6	6
Tug-Shuttle Dock.	3	3
Propel. Tanks	38	25
Interface Panels	11	10
Tank Insulation	64	47
Main Prop.	62	31
Aux. Prop.	110	55
Elect. Power	34	29
Avionics	30	15
Total	$368K	$231K

10. PROPELLANTS AND GASES

a. Definition

Refers to the costs of propellants and gases consumed by the Tug vehicles during the operations phase, including the manufacturing costs of all propellants and gases used by the Tug vehicles. Includes allowances for boil-off, chill-down, and other losses.

b. Cost Analysis

The bottoms-up method of determining the cost of the propellants and gases was the same as used by the CER, viz., total propellant and gas used times a cost per pound. The CER costing equation is described in Appendix A.

11. RANGE AND BASE SUPPORT

a. Definition

The definition of range and base support as defined by the CER includes the indirect costs of range services that support the direct launch and maintenance operations. Covered are range safety and control; shop and repair services; standards and instrument calibration; base services such as food, mail, reproduction, security, fire protection, utilities, communications, transportation, health and custodial services, and logistics support.

The "institutional" costs that are estimated in the following paragraphs represent the total costs of operating and supporting the range and base at the eastern and western sites. No attempt was made to define that portion of the total cost that could be attributed to support as defined by the CER.

b. Cost Analysis

A brief survey was made of recent budget provisions for the two test ranges - ETR and WTR. It was determined that FY 1972 budgets were \$120.3M and \$68.5M, respectively, including civilian pay. Military pay was

not directly identifiable, but other sources indicated approximately \$7M for WTR, which on a budget ratio basis would give about \$12M for ETR. In addition, budget requests for Defense Communications System support were additive and the WTR amount was \$0.9M. Again, the ETR amount was estimated at \$1.6M. These figures sum to \$133.9M for ETR and \$76.4M for WTR.

The traffic supported by each range is comprised of both missile and space launches. It has been reported that only 25 percent of the launches at VAFB are space vehicles. Similarly, some of the traffic at ETR is of missile launches and, in the absence of definitive data, a distribution of 75 percent space, 25 percent missile will be assumed. Space traffic support budgets of \$100.4M at ETR and \$19.1M at WTR can be projected from these traffic mixes.

The current cost of base support at KSC was estimated to be \$80M. The amount was determined through research of the Congressional NASA budget hearings which gave totals of \$95M for FY 1970 and \$85M for FY 1971 for the category of "support services contracts" - approximately equivalent to base support activity. A 1972 figure of \$80M was chosen as a reasonable extrapolation of the 1971 budget. A further extrapolation to \$60M was assessed as representative of support for the fully mature and operational STS.

The base support at VAFB was reported to be \$20M during an earlier survey at the base. However, in contrast to KSC, virtually no major facilities exist for STS adaptation at VAFB and will have to be added. It was assumed that the support required would roughly compare to that support presently being supplied and thus STS base support at VAFB was estimated as \$20M.

The Tug portion of the above costs was distributed on the basis of the ratio of Tug flights to total Shuttle flights at each base and a sharing of costs with the Shuttle for the combination flights. The flight totals used in that distribution were: ETR - 398 STS, 240 with Tug; WTR - 218 STS, 64

with Tug. The ratios were then applied to the range and base support totals and resulted in annual Tug range and base support costs of $48.3M at ETR/KSC and $5.7M at WTR/VAFB.

12. TUG OPERATIONS COST SUMMARY

a. Direct Operating Costs

The Tug direct operating costs are presented in Table 3-7 in the units of the method used to generate the bottoms-up estimate. For instance, the Ground Operations covering launch, recovery, and maintenance/refurbishment were estimated in the units of manhours per flight. It was concluded that a dedicated Tug crew (at each launch site) of 52 men for IOC and 37 men for OC was a preferred mode of operation compared to a manpower pool. Both approaches are presented in Table 3-7. As can be noted, the dedicated crew is more costly in total yearly manhours; however, it is the minimum number of personnel composed of the skills required to accomplish all the ground operations tasks.

The spares costs noted in Table 3-7 were derived in a previous Tug Refurbishment Cost Study (Ref. 1) and are presented in summary in Section 3.D.9. The propellant costs were determined using the CER as noted in Appendix A.

Manpower requirements to support Command and Control were defined in Section 3.D.3. It is to be noted that the 80 and 24 men required for the IOC and OC phases, respectively, represent a major change in the mode of space operations but are in keeping with the goal of significantly reducing the cost of space transporation.

b. Indirect Operating Costs

The Tug indirect operating costs are presented in Table 3-8 in the units of the bottoms-up estimating methodology. The Facility and Equipment Maintenance entry of $3,112 K/yr is the sum of Tug Facilities Maintenance and Tug Ground Support Equipment Maintenance for both KSC and WTR (see

Table 3-7. Tug Direct Operating Costs, Bottoms-Up Estimate

	Manpower Pool		Dedicated Tug Crew	
	IOC	OC	IOC	OC
Ground Operations				
Launch	384 mhr/flt[1]	256 mhr/flt		
Recovery	156 mhr/flt	104 mhr/flt	104 myr/yr[2]	74 myr/yr
Vehicle Maintenance	3,546 mhr/flt	2,482 mhr/flt		
Spares	\$368 K/flt	\$231 K/flt	\$368 K/flt	\$231 K/flt
Propellants	\$11 K/flt	\$11 K/flt	\$11 K/flt	\$11 K/flt
Flight Operations				
Command and Control	80 myr/yr	24 myr/yr	80 myr/yr	24 myr/yr

[1] Manhours per flight.
[2] Manyears per year, 2 sites.

Table 3-8. Tug Indirect Operating Costs, Bottoms-Up Estimate

	IOC	OC
Facility & Equipment Maintenance	$3,112K/yr	$3,112K/yr
Replacement Training ($17K/man)	26 men/yr	18.5 men/yr
Engineering Support ($46K/myr)	93 myr/yr	71 myr/yr
Program Integration & Management ($46K/myr)	25 myr/yr	20 myr/yr

Section 3.D.5). Replacement training is for the ground crew only and results in 25 percent of the crew requiring training each year due to attrition. The training cost as noted in Section 3.D.4.b is $17,250 per man. Engineering Support manpower and Program Integration and Management manpower are derived in Sections 3.D.7 and 3.D.8, respectively. The rate used to calculate the yearly and per flight costs is $46,000 per man-year.

c. Institutional Base Costs

Table 3-9 presents the Institutional Base cost estimates for the STS era of space flight operations. These costs are derived from several sources as noted in Sections 3.D.3.b and 3.D.11.b and are presented for information purposes only. These institutional areas involve the costs of operating the bases on which the launch sites are located, the down-range facilities, the mission control centers, and the associated tracking nets for flight support. Additionally, both NASA and DOD facilities are involved as noted in Table 3-9. Both the STS Estimate and the Tug Estimate are allocations based upon the estimated percentage of use considering missile and space launches and Shuttle-only launches.

d. Tug Turnaround Costs

Included in Table 3-10 are all the per flight and yearly operations costs that could in any way be related to Tug Turnaround Costs. The cost data presented have been derived by applying the following cost factors to the data presented in Tables 3-7 and 3-8.

Dedicated Crew Cost	$34,000/man-year
Training Cost	$17,250/man
Command/Control	$46,000 man-year
Engineering Support	$46,000/man-year
Program Integration/ Management	$46,000/man-year

Table 3-9. Tug Institutional Base Costs
($ Millions/yr)

	Current Budget	STS Estimate	Tug Estimate
Range and Base Support			
AFETR	$134M	$100M	$48.3M
KSC	$ 71M	$ 60M	
AFWTR (SAMTEC)	$ 76M	$ 19M	$ 5.7M
VAFB	$ 20M	$ 20M	
Mission Support			
AFSCF (including RTS)	$150M	$ 25M	$ 8.3M
MCC (including STDN and MSFN)	ASSUMED EQUAL TO AFSCF ESTIMATE		

Table 3-10. Tug Turnaround Cost Estimate Summary — 304 Tug Flights, 12-Year Program

Direct - 10^3 dollars/flight*	Manpower Pool		Dedicated Tug Crew	
Ground Operations	IOC	OC	IOC	OC
Launch	7 *	4	140	100
Recovery	3	2		
Vehicle Maintenance	60	42		
Spares	368	231	368	231
Propellants	11	11	11	11
Flight Operations				
Command and Control	146	44	146	44

Indirect - 10^3 dollars/yr **	IOC	OC
Facility & Equip. Maint.	3,112 **	3,112
Replacement Training	449	319
Engineering Support	4,278	3,266
Program Int. & Mgt.	1,150	920

Institutional - 10^3 dollars/yr **	
Range & Base Support	54,000 **
Mission Support	16,600

Application of these rates considering two launch sites and an average of 25.3 total launches per year results in the following conclusions.

1. The total direct costs of an average Tug turnaround, i.e., landing-to-launch, are $519K and $342K for the IOC and OC phases of the flight program, respectively.
2. The total direct operational costs for Tug missions, i.e., launch-to-launch including flight operations, are $665K and $386K for IOC and OC, respectively.
3. The total direct and indirect operational costs for Tug missions, i.e., launch-to-launch including flight operations, are $1,020K and $687K for IOC and OC, respectively.

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4. STS ABORT MODES AND EFFECTS STUDY

A. STUDY OBJECTIVE AND APPROACH

The overall objective of this study was to assess the major effects and impacts of abort on the flight and ground elements of the STS, viz., the Orbiter, Tug, Payload, Ground Support, and Flight Support, including Facilities and Equipments. The main emphasis of this study was on the identification of Tug-related abort effects and impacts, i.e., those that are caused by the Tug and those that affect the Tug. The performance capability of the Tug vehicle with either degraded main engine thrust or reaction control system thrust was analyzed as a special emphasis task. Also, a cursory analysis was made to assess the on-board data management system requirements for performing all Tug-related abort decisions and operations on board the Tug vehicle.

The approach used in this assessment was first to define the baseline STS elements and a baseline mission. Abort regimes were then defined for all phases of the baseline mission from liftoff to reentry. The next step was to determine the gross effects on the STS elements of an assumed abort-producing failure in each flight element for each abort regime. This step provided an overview of the abort problem and ensured that all general categories of abort were addressed. The next step in the assessment was to define the actual failure or failure modes and then relate these to impacts on the STS elements. Because of the state of the design of the Orbiter and Tug vehicles and the many diversified payloads that are planned to be orbited by the STS, a detailed analysis of all the possible failure modes of these STS elements was not attempted. Therefore, the failure analysis was limited to a gross assessment of the possible failure modes and hazards and was made with the following limitations and assumptions: (1) the cause of failure was generally not isolated beyond the subsystem level, (2) no numerical probabilities were calculated, and (3) only payload types that require a Tug mission for payload replacement were considered.

B. BASELINE VEHICLE DESCRIPTIONS

The Space Transportation System for this study is assumed to be comprised of a two-stage Space Shuttle system and a reusable upper stage. The Shuttle operates between the surface of the earth and low earth orbit, and the upper stage operates between low earth orbit and earth synchronous orbit. The descriptions of the baseline vehicles used in this study are provided in Ref. 4 and 5. The Shuttle description is the same as that presented by North American Rockwell in their November 1972 Space Shuttle System Summary and Program Requirements Review briefing. The Tug description is the June 26, 1972 version of the NASA MSFC Tug definition. A brief description of the Shuttle system and the upper stage is provided below.

The Space Shuttle system consists of the reusable, manned Orbiter, an expendable external tank, and two recoverable, unmanned solid rocket boosters integrated as shown in Figure 4-1 (from Ref. 4). The Orbiter carries the crew and payload and is mounted piggyback to the single, expendable tank which contains all of the hydrogen and oxygen propellants utilized by the Orbiter rocket engines during the ascent phase of flight. The two solid rockets that comprise the booster are located under the wings of the Orbiter and are attached directly to the propellant tank.

Liftoff thrust is provided by parallel burning of the solid rocket booster (SRB) and Orbiter main engines. Guidance and control through the boost phase is provided by Orbiter main engine thrust vector control (TVC), SRB TVC, and elevon deflection. At SRB staging, auxiliary rockets are fired to accelerate the expended cases from the vehicle at one g. The SRB cases follow a ballistic trajectory after separation, are decelerated by parachute, and are recovered after water landing. The three Orbiter main engines continue firing to orbit injection at 93 km (50 nmi) altitude.

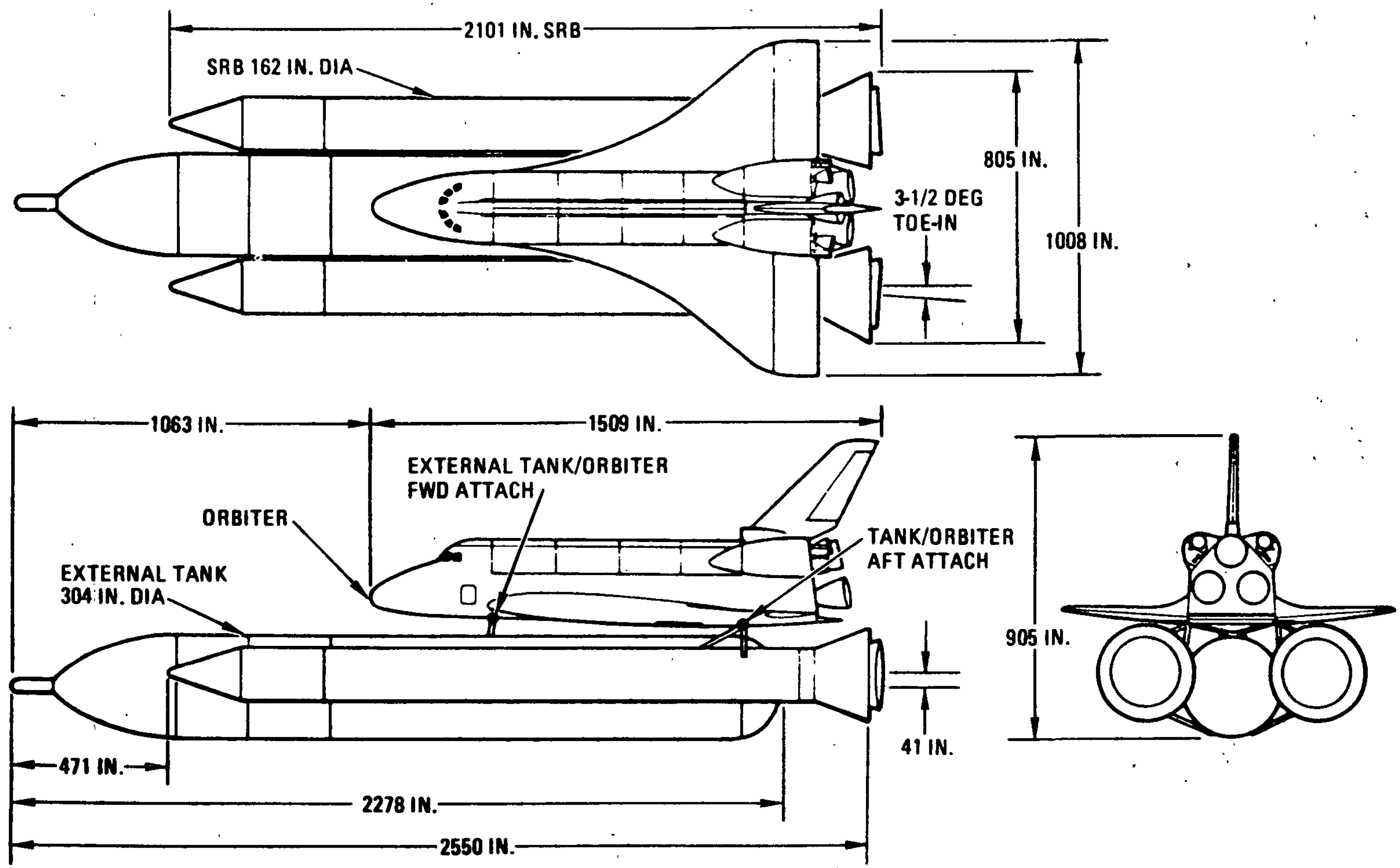

Figure 4-1. Space Shuttle Vehicle (PRR Baseline)

The capability for intact Orbiter recovery in the event of premature mission termination is provided throughout the entire mission sequence. Intact abort capability is provided during the first 30 seconds[1] by the SRBs with TVC. The SRBs will provide sufficient control and thrust to continue ascent until a safe altitude for abort glideback is achieved. In the abort regime from 30 seconds of flight to orbital injection, return to launch site is accomplished by Orbiter separation and glideback, or by continued flight using the orbital maneuvering system (OMS) and the main engines into a direct return or once-around abort trajectory. The external tank is separated after injection, and its de-orbit motor is fired to place it into a trajectory with impact in a designated ocean area. Table 4-1 gives the Shuttle launch abort modes.

The Orbiter vehicle circularizes in orbit at the appropriate altitude using the OMS and then performs on-orbit mission operations. On completing mission operations, the OMS is fired to initiate de-orbit and establish an entry trajectory. The Orbiter achieves required cross range by energy management, and returns to base where the vehicle is landed in a manner similar to that of high performance aircraft.

The upper stage (Tug) is a high performance vehicle designed to operate as a ground-based vehicle. The Tug is a single stage vehicle utilizing liquid hydrogen and liquid oxygen as propellants and is capable of performing a round-trip mission from low earth orbit to geosynchronous orbit with a 1361 kg (3000 lb) payload. The Tug is deployed by the Orbiter in low earth orbit with a payload attached, ascends to geosynchronous orbit, deploys the up payload, retrieves the down payload, returns to the near vicinity of the Orbiter, redocks with the Orbiter, and is returned to earth. The overall configuration of the baseline Tug is shown in Figure 4-2 (from Ref. 5).

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[1] Thrust termination has recently been eliminated from SRB by the NASA Shuttle Program Office. Abort sequence has changed as a result. The effects of this change are noted in subsequent paragraphs.

Table 4-1. Shuttle Launch Abort Modes

Mode	Time From Liftoff (sec)	Description
I[1]	$0 < t < 30$	a. Launch vehicle continues ascent until sufficient altitude and velocity are reached so that the Orbiter can glide back to the launch site. b. Sufficient control power exists so that a safe intact abort can be made from the following failures: 1. Thrust loss of 1, 2, or 3 Orbiter main engines. 2. Loss of control from 1, 2, or 3 Orbiter main engines (fail to null). 3. Loss of one SRM TVC (fail to null).
II[1]	$30 < t < 90$	a. Sequence of events for aborts during this time period is as follows: 1. Shutdown Orbiter engines. 2. Thrust terminate SRMs.[2] 3. Separate Orbiter. 4. Orbiter glideback to the launch site. b. Safe separation of the Orbiter will require vehicle attitudes other than those sought by the guidance system during powered ascent.

[1] Modes I through IIIa can be combined into single abort regime due to deletion of SRM thrust termination.

[2] Capability deleted by NASA Shuttle Program Office.

Table 4-1. Shuttle Launch Abort Modes (concluded)

Mode	Time From Liftoff (sec)	Description
IIIa[1]	$90 < t < 124.9$	a. Sequence of events for aborts during this time period are as follows: 1. Thrust terminate SRMs.[2] 2. Separate SRMs. 3. Continue burning Orbiter engines in a powered return to the launch site maneuver. b. Nominal burnout of the SRMs occurs at 124.9 sec.
IIIb	$124.9 \leq t < 259$	a. Same as Mode IIIa except that the SRMs have burned out and have been jettisoned at 124.9 sec. b. Both Mode IIIa and IIIb can be performed with one Orbiter engine out.
IV	$259 < t < 373$	a. Orbiter aborts to a once-around orbit. This can be done with one Orbiter engine out.
V	$373 < t < 532$	a. Orbiter can insert into a stable orbit even with one engine out.

[1] Modes I through IIIa can be combined into single abort regime due to deletion of SRM thrust termination.

[2] Capability deleted by NASA Shuttle Program Office.

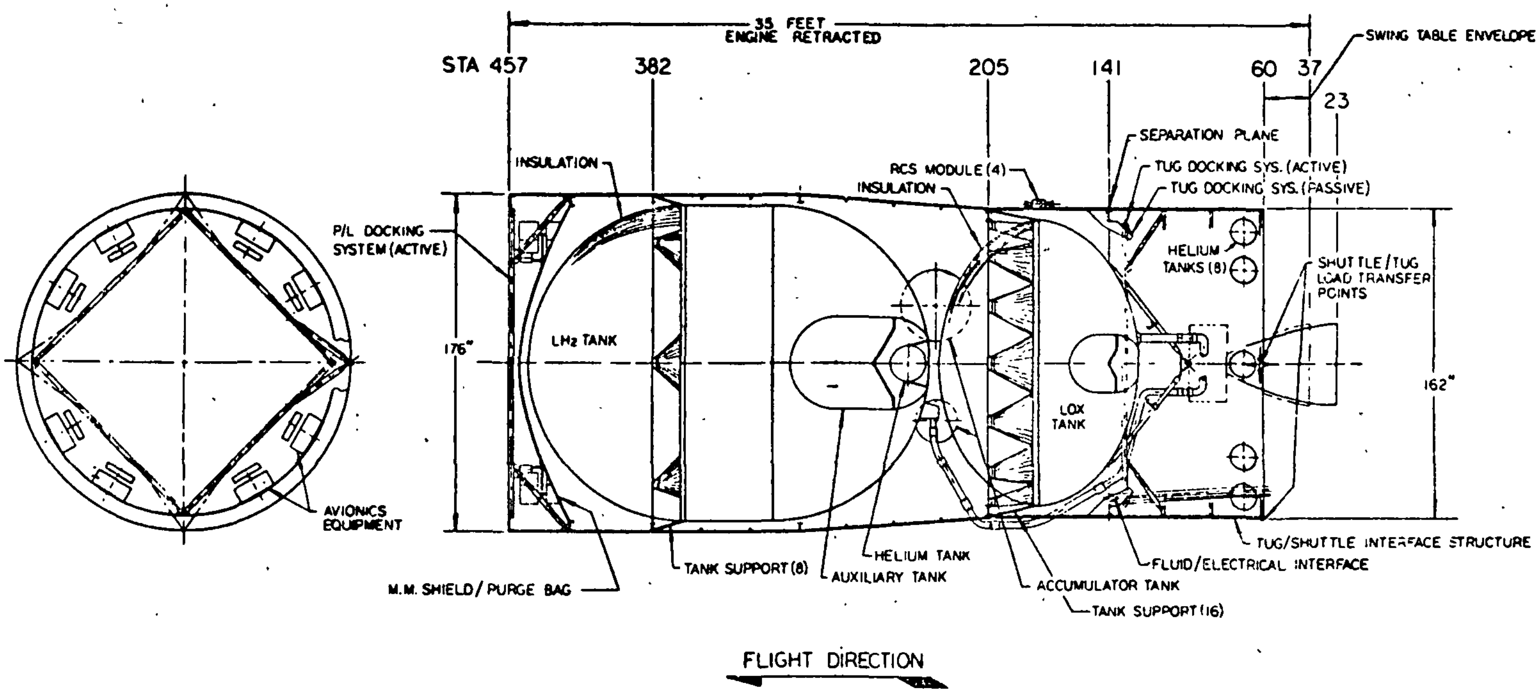


Figure 4-2. Baseline Tug Overall Configuration

Since the payloads to be put into orbit by the STS in the 1980s are many and diverse, no particular baseline was assumed for this study. The only assumption made was that the payload was designed to be deployed and retrieved by the STS. The possible failure modes and hazards created by the Shuttle, Tug, and payloads were synthesized from the data contained in Ref. 12 through 28.

C. BASELINE MISSION

The baseline mission is as defined in Ref. 5. The mission assumes that a 1361 kg (3000 lb) payload is deployed and retrieved at geosynchronous altitude and that the up and down payload is separated by approximately a 10-deg separation angle or a separation distance of 7408 km (4000 nmi). The mission profile is shown in Figure 4-3. The mission scenario is presented in the following paragraphs.

The Orbiter injects into a 93 by 185 km (50 by 100 nmi), 28.5 deg elliptical orbit. The Orbiter coasts to apogee and circularizes, coasts for one revolution in the 185 km (100 nmi) circular orbit, and then injects into a 185 by 296 km (100 by 160 nmi) orbit. The Orbiter coasts to apogee and then circularizes at 296 km (160 nmi). The Tug is then checked out and deployed. The Tug phases in the 296 km (160 nmi) orbit for up to 12 hours for longitude correction. After phasing, the Tug injects into a 296 by 35,862 km (160 by 19,364 nmi) transfer orbit with a 2-deg plane change at perigee. The Tug coasts to apogee and makes a 26.5 deg plane change and circularizes. The Tug then performs orbit trim maneuvers and coasts in synchronous equatorial orbit for one revolution prior to payload deployment.

Subsequent to payload deployment, the Tug performs phasing orbit maneuvers for up to 48 hours to rendezvous with the returning payload. The Tug then docks with the returning payload and phases in orbit for up to 5.6 hours to obtain the correct nodal crossing. The Tug performs a 26.5 deg plane change and injects into a 315 by 35,862 km (170 by 19,364 nmi) transfer orbit. The Tug coasts to perigee, makes a 2-deg plane change and injects

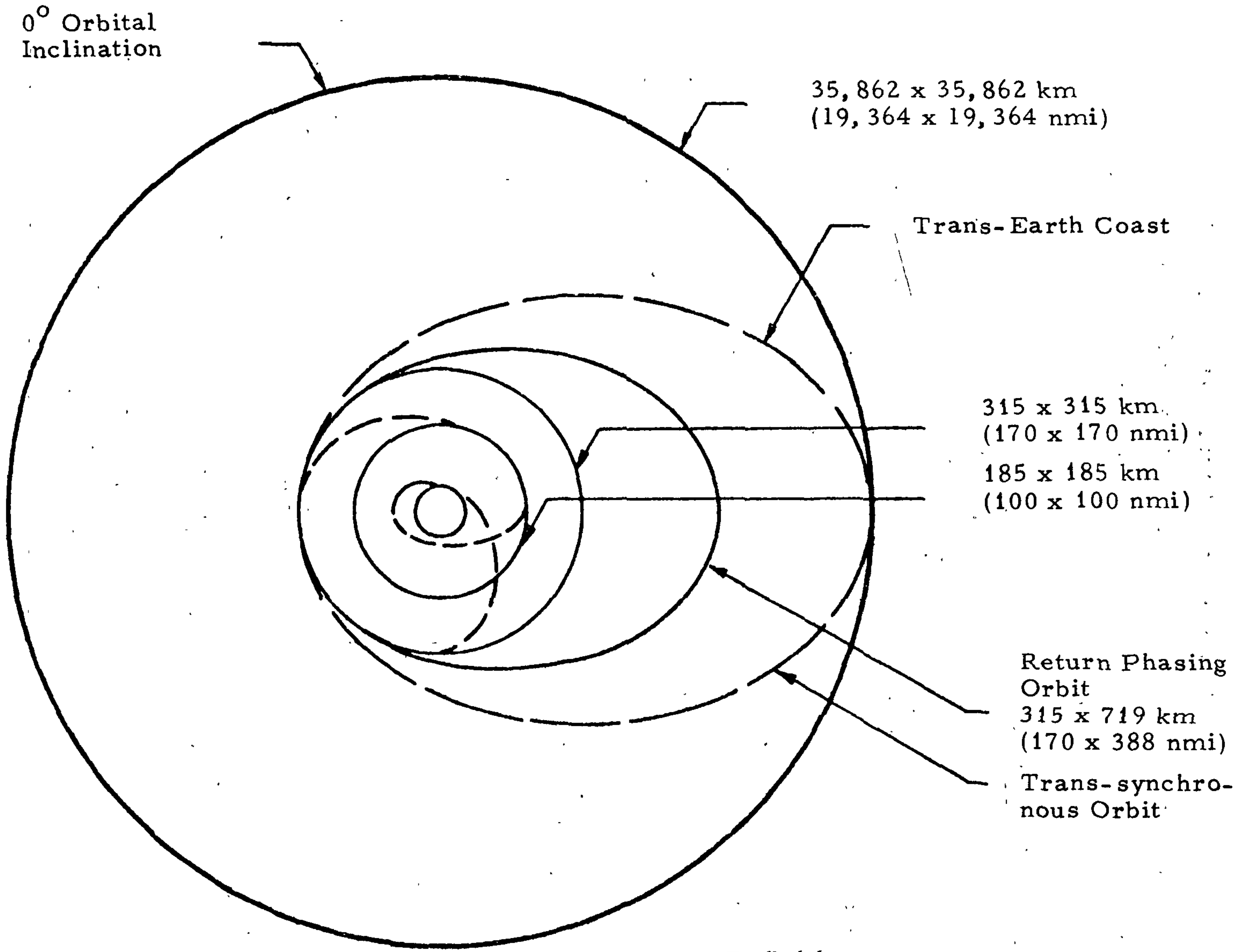


Figure 4-3. Baseline Mission Definition

into a 315 by 719 km (170 by 388 nmi) phasing orbit. The Tug phases for one revolution and then circularizes in a 315 km (170 nmi) orbit. The Orbiter performs the terminal phase rendezvous and docking. The Orbiter then phases and returns to the launch site.

D. STS ABORT ASSESSMENT

The impact of an abort on the various STS elements is dependent on the failure that caused the abort, the STS element in which the failure occurred, and the time in the mission at which the failure occurred. Abort regimes for all phases of the baseline mission from liftoff to reentry were defined. The gross effects on the STS elements of a failure in each flight element for each abort regime were then determined. No definition of the actual failure was assumed. This procedure provided an overview of the abort problem and ensured that all general categories of abort were addressed. The actual failures or failure modes were then determined and related to impacts on the STS elements.

1. STS ABORT REGIMES

The baseline mission profile was divided into 16 abort regimes which are defined in the following paragraphs. The first five of these represent the ascent abort regimes for the Shuttle.

a. Regime I - $0 < t < 30$ sec. This abort regime covers the first 30 seconds after liftoff. If a Shuttle abort occurs during this time frame, there is enough thrust available to continue ascent to a sufficient altitude for glide back to the launch site.

b. Regime II - $30 < t < 90$ sec. If a Shuttle abort occurs during this period, the engines are shut down and the Orbiter glides back to the launch site.

c. Regime IIIa - $90 < t < 124.9$ sec. For an abort during this time span, the solid rocket motors (SRMs) are thrust-terminated and the Orbiter engine's burn is continued for a powered return to the launch site.

d. Regime IIIb - 124.9 < t < 259 sec. This abort mode is the same as IIIa except the SRMs have burned out and are jettisoned at 124.9 sec.

e. Regime IV - 259 < t < 363 sec. The Orbiter aborts to a once-around orbit.

f. Regime V - 373 < t < 532 sec. The Orbiter can thrust into a stable orbit 93 by 185 km (50 by 100 nmi)

g. Regime VI. This regime is comprised of the time that the Orbiter coasts in the 93 by 185 km (50 by 100 nmi) elliptical orbit to the end of the burn at apogee.

h. Regime VII. This abort regime consists of the time that the Orbiter coasts in the 185 km (100 nmi) circular orbit to the end of the burn for injection into a 185 by 296 km (100 by 160 nmi) orbit and ends

i. Regime VIII. This regime starts with the end of the injection burn into the 185 by 296 km (100 by 160 nmi) orbit and ends when the Orbiter has circularized at the 296 km (160 nmi) apogee.

j. Regime IX. This abort regime starts with the Orbiter coast in the 296 km (160 nmi) orbit and ends when the Tug has been deployed.

k. Regime X. The abort regime covers the time that the Tug is coasting in the 296 km (160 nmi) circular orbit to the end of the first burn into the 296 by 35,862 km (160 by 19,364 nmi) transfer ellipse.

l. Regime XI. This abort regime covers the time from the end of the burn to inject into the 296 by 35,862 km (160 by 19,364 nmi) transfer ellipse to the end of the circularization burn at apogee.

m. Regime XII. This starts with Tug coast in the circular orbit and ends with payload deployment.

n. Regime XIII. This covers the time from the end of payload deployment to the end of the first de-orbit burn and includes payload retrieval.

o. Regime XIV. This regime covers the time from the end of the burn to inject into the 315 by 35,862 km (170 by 19,364 nmi) elliptical transfer orbit to the end of the burn at 315 km (170 nmi) perigee to inject into the 315 by 719 km (170 by 388 nmi) phasing orbit.

p. Regime XV. This represents the time that the Tug is in the low earth phasing orbit. It ends with the circularization burn at 315 km (170 nmi).

q. Regime XVI. This regime covers the time from the end of the circularization burn at 315 km (170 nmi) and ends with the completion of Orbiter/Tug docking.

2. STS GROSS ABORT EFFECTS

For each of the abort regimes defined in the previous section, the gross effects on each of the STS elements, viz., the Orbiter, Tug, payload, and ground facilities of an abort-producing failure in one of the STS flight elements were assessed. This assessment was not concerned with the actual failure mode of the element, but merely assumed that a failure had occurred in the element which resulted in an abort. (Subsequent sections of this report address the effect of specific failures on abort.)

At present, the only Shuttle failures that have been identified that would result in an abort during the powered ascent phase of the Shuttle flight are those concerned with the Orbiter main engines and solid rocket motors (Table 4-1). Detection difficulty, the inability to rapidly evaluate damage, and the lack of viable alternatives for corrective action limit the failures that can be considered to require an abort in this phase of the mission. The types of Tug or payload failures that would dictate a Shuttle abort are those that could jeopardize the safety of the crew or result in damage to the Orbiter of such a magnitude as to prevent the Orbiter from continuing to orbit. Because of the time required to abort the ascent phase and return to a landing site, the hazardous condition created by a Tug or payload failure may become worse if the Orbiter returned to a landing site instead of continuing on to orbit. Hence, each failure mode would have to be evaluated to determine the safest abort procedure.

For this abort assessment, it was assumed that no aborts (immediate return to landing site) would be dictated by a Tug or payload failure during powered Shuttle ascent flight. All Tug or payload failures were assumed to be fail-safe in nature relative to the Orbiter. In the event of a Tug or payload failure, the Orbiter would continue on to a stable orbit at which time an abort

procedure could be initiated dependent on the type of failure. This conclusion is supported in the next section which addresses the effects of actual failures in that no Tug or payload failures were uncovered that would appear to dictate a Shuttle abort during ascent. However, since the subjects of failures and aborts are dependent upon the depth of definition of the vehicles involved, this conclusion should be continuously evaluated as the designs progress.

The results of the gross abort effects assessment are tabulated in Table B-1 of Appendix B. During each abort regime, a failure in each of the flight elements was assumed to occur; however, only one flight element at a time was assumed to have incurred a failure. Listed in the table are the abort regime, the flight element in which the failure occurred, the action taken as a result of the failure, and the effects on the STS elements. In the 63 cases listed, there are only a few different gross effects on each of the elements. This is a result of the similarity of the abort actions taken in many of the abort regimes. The different gross effects listed in Table B-1 on each of the STS elements are summarized in Table 4-2. In addition to the effects listed in Table B-1, Table 4-2 also includes effects on the flight support system of the ground element. These effects refer to the need for communication between the ground and flight elements for abort knowledge and actions.

The gross effects on the Orbiter that are summarized in Table 4-2 could result in both operational and design impacts. The first effect means that the Orbiter would have to be designed to land with a Tug that is fully fueled or provide for rapid dumping of Tug propellants. This is a result of the abort that could occur in abort regimes wherein there is a limited amount of time available to dump the Tug propellants. The second effect, viz., additional phasing orbit maneuvers, may dictate that the Orbiter OMS system would always be loaded to capacity for all missions to provide the maximum on-orbit ΔV capability. The third and fourth effects should have no impact on the Orbiter other than possible delays in the ground turnaround cycle due to unscheduled returns.

The gross effects on the Tug could have some definite impacts on the design and the operational requirements of the Tug. The first effect, listed

Table 4-2. Abort Effects Summary

Element	Effect
Orbiter	a. Land with fully or partially fueled Tug. b. Perform additional phasing orbit maneuvers for rendezvous with out-of-phase Tug. c. Return to earth earlier than scheduled. d. Return to earth empty.
Tug	a. Land full or partially full. b. Return to Orbiter earlier or later than scheduled. c. Determine proper phasing for unscheduled return to Orbiter parking orbit. d. Remain in low earth parking orbit for extended time for retrieval by subsequent Orbiter flight.
Payload	a. Return to earth earlier or later than scheduled. b. Deployed in off-nominal orbit.
Ground	a. Handle fully or partially fueled Tug. b. Altered flow of flight elements through ground turnaround cycle. c. Abort status of flight elements is provided to ground for executive confirmation and action. d. Unscheduled communications with flight elements to coordinate abort activities.

in Table 4-2, viz., land full or partially full, means that the Tug should be designed to land full and have the capability to be drained in the horizontal position or be capable of rapid propellant dumping. The second and fourth effects impact the time that the Tug must stay on orbit. To survive this additional on-orbit stay time, it may be necessary for certain Tug systems to have extended mission capability to permit longer stay times in the low earth parking orbit for Orbiter pick up. The third effect, viz., phasing determination, means that the Tug should be able to do some mission planning either autonomously or with the aid of the ground.

The most severe effect identified for the payload is that it may be deployed in an orbit which is very much different from that in which it was designed to operate. The payload would have to stay in this off-nominal orbit until retrieval by a subsequent Tug flight. This would mean that the payload would have to survive in this orbit and be able to stabilize itself for Tug retrieval.

The effects on the ground element could impact the design of the support facilities and the operational timelines. The ground safing area may have to be capable of handling a Tug that is fully or partially fueled. The altered flow of the flight elements through the ground turnaround cycle could impact the physical size of the facilities.

3. STS FAILURE MODE EFFECTS

In the previous section, an abort assessment was made by assuming abort-producing failures to occur in each of the flight elements without any assumptions relative to the actual failures. The resulting effects on the STS were then identified. This provided an overview of the abort situation for all mission phases. In the following paragraphs, failure modes are identified for each of the flight elements and the resulting abort effects determined. This approach provides more insight into the abort problem in certain areas.

Because of the state of the design of the Orbiter and Tug vehicles and the many diversified payloads that are planned to be orbited by the STS, a detailed analysis of all the possible failure modes of these STS elements was not possible. Therefore, the failure analysis was limited to a gross assessment of the possible failure modes and hazards. This assessment was made with the following limitations and assumptions: (1) the cause of failure was generally not isolated beyond the subsystem level, (2) no numerical probabilities were calculated, and (3) only payload types that require a Tug mission for orbit injection/replacement were considered.

The information presented in this section was derived from the Shuttle and Tug information contained in Ref. 4 through 10 and the experience gained from related programs as described in Ref. 11 through 24. A review of these references indicated that most of the major failure modes have been addressed in the baseline vehicle designs. The areas that were selected for further assessment are presented in Tables 4-3 through 4-6.

a. Failure Classification

As an aide in evaluating the various emergency situations and their subsequent effect on the STS elements, the failure modes of the flight elements were arranged into the following five groups:

1. Group 1. Areas where redundancy is impractical. Examples are the Orbiter heat shield and the basic vehicle structure.
2. Group 2. Areas where failure results in degraded operation. An example is the Orbiter main propulsion system where partial thrust is available in the event of a single engine failure.
3. Group 3. Areas where redundancy was not utilized in the design. An example is the Tug fuel cell subsystem.
4. Group 4. Areas where partial redundancy was used. An example is the Tug communication subsystem where everything except the filter, hybrid junction, and RF multiplexer are redundant.

5. Group 5. Areas where rapid fault detection and redundancy switching are required. Examples of this area of concern are the attitude control subsystems of the Orbiter and Tug during the time of docking.

The major failure modes and hazards are described in the subsequent paragraphs. A brief description of the failure, the gross effects of this failure, and, in some cases, possible abort procedures are discussed.

b. Shuttle Failures

(1) Major Failure Modes

Table 4-3 is a listing of the major failure modes of the Shuttle. No major group 3 or group 4 failure modes were identified.

(a) Group 1. Damage to the heat shield and structure areas generally result from a collision in space or from an internal accident. A procedure for visually inspecting the Orbiter with the Tug TV cameras could provide a means of assessing any external damage to the Orbiter heat shield. In the event of heat shield damage, a less severe reentry trajectory, e.g., less cross range, may be advisable.

A mechanical failure of the manipulators during Tug deployment or retrieval could result in damage to the flight elements or prevent the operation from being completed. According to Ref. 6, the manipulators can be jettisoned from the Orbiter if necessary.

(b) Group 2. In the event of a failure in the main propulsion system or the solid rocket engines, an abort procedure as described in Table 4-1 would be followed.

The crew could be in danger if the cabin pressure became low, insufficient oxygen were available, or the atmosphere became contaminated. Generally these dangers would not lead to an early abort, since these deficiencies are difficult to assess during the early launch periods. These problems could be greatly reduced if the crew wore spacesuits during the early launch periods. Injury or major sickness of a crew member may require an early return of the Orbiter.

Table 4-3. Shuttle Failure Modes of Concern

Area	Failure Mode	Time Phase	Causes	System Effects	Comments
Main Propulsion System	Loss (partial loss) of one or more engines.	During powered flight.	Engine, engine control, fuel line failures.	Inability to achieve orbit.	Abort procedures have been developed. See Table 4-1.
Solid Rocket Motors	Loss (partial loss) of thrust either engine.	During powered flight.	Flame out, defective material.	Inability to achieve orbit.	Abort procedures have been developed. See Table 4-1.
Life Support	Insufficient oxygen pressure or contaminated atmosphere.	All.	Gas leakage, cabin leaks, fires, structural damage.	Danger to survival of the crew.	Immediate abort may be required, if life support is insufficient. The wearing of pressure suits by the crew should be considered during boost phase and be available at other times. Early mission termination may be required, when danger is not immediate.
Crew	Crew health, injury.	On-orbit.	Accident, sudden illness.	Danger to survival of crew.	Early return may be necessary to save crew member's life.
Attitude Control	Temporary loss of control.	During Tug release, capture.	Amplifier short, intermittent operation, extraneous outputs.	Damage to the Tug or Orbiter or possible Tug loss.	Although redundancy exists, almost immediate fault detection and redundancy switching is required during this time period to avoid potential danger.
Manipulators	Unable to release/capture Tug. Release of Tug in wrong direction.	Tug release, capture.	Mechanical or electrical failure of manipulator system.	Damage to Tug and/or payload. Possible Orbiter damage.	If the Tug is stuck on the manipulator, both can be ejected (Ref. 6). Although redundancy exists in the electrical control, almost immediate fault detection and redundancy switching is required during this, time to avoid potential damage.
Heat Shield and Structure	Damage to the heat shield or structure.	Before reentry.	Damage to heat shield or structure by impact with Tug or other object.	Excess heat or possible collapse, if normal reentry pattern is followed.	If damage is known to have occurred, a less severe reentry pattern could be followed. It may be unsafe to carry a Tug and/or payload in such an Orbiter during reentry.

(c) Group 5. Failure in attitude control (A/C) during release or pickup of the Tug could result in damage to either the Orbiter or the Tug, if the fault were not detected and corrected almost immediately. A badly damaged Tug might have to be abandoned. If the Orbiter were damaged, immediate return to earth might be required. Since the A/C is a triple redundant unit, ways could be found, i.e., majority voting, during this critical time period to ensure adequate fault detection and redundancy switching.

Momentary failure of the manipulator control electronics could cause the same problems as with the A/C during this critical time period.

(2) Secondary Failure Modes

For this assessment, secondary failure modes are defined as those failures having a low failure frequency (redundancy, or backup, is available) and failures where short-term outages are not mission-critical.

The orbital maneuvering system (OMS) and the reaction control system each have considerable redundancy provided against failure. If the OMS were to fail (or be badly degraded) the Tug might still be deployed by taking advantage of the Orbiter flight pattern, i.e., deploy the Tug near apogee of the 93 by 185 km (50 by 100 nmi) Orbiter orbit. An alternate Orbiter reentry mode might also be required.

c. Tug Failures

(1) Failure Modes

Table 4-4 is a listing of the failure modes of the Tug. Certain areas of these modes are discussed below.

(a) Group 1. Damage to the Orbiter/Tug docking mechanisms may prohibit the deployment or retrieval of the Tug. This damage may result from excessive closing rates between the Orbiter and Tug during docking or from an off-nominal deployment operation. The effect is dependent on when the failure occurs. If the failure occurs prior to deployment, then the mission must be aborted and the Orbiter/Tug/payload returned to earth. If the failure

Table 4-4. Tug Failure Modes of Concern

Area	Failure Mode	Time Phase	Causes	System Effects	Comments
Main Engine	Loss of thrust, incorrect thrust.	During major burns.	Activators, pumps, lines, and control failures.	Mission abort or Tug loss.	The auxiliary propulsion system (APS) could be used in the event of a failure in the main propulsion system provided the APS has access to the main propulsion fuel.
Auxiliary Propulsion System	Incorrect thrust.	During payload docking.	Loss of control on some thrusters.	Damage to or loss of payload or Tug.	It is difficult to monitor this type of failure and damage may be caused before redundancy can become effective. It may be unsafe for the Orbiter to capture a damaged Tug (and payload).
Attitude Control	Temporary loss of control.	During payload release/capture, Tug/Orbiter docking.	Amplifier short, intermittent operation, extraneous outputs.	Possible loss of or damage to payload and Tug.	Although redundancy exists, almost immediate fault detection and redundancy switching may be required during this time period. To avoid potential damage, majority voting or command override could be considered.
Orbiter/Tug Structural Interface	Improper operation of docking mechanism.	During Tug release/capture by Orbiter.	Failure of or damage to the Tug docking mechanism.	Unable to release/capture Tug.	Part or all of the mission may be aborted. Procedure for determining the status of the Orbiter/Tug latching mechanism is required. It may be necessary to abandon the Tug if it cannot be secured inside the Orbiter bay.
Tug/Payload Structural Interface	Improper operation of payload deploy/retrieval mechanism.	During payload release/capture.	Failure or damage to the Tug payload release/capture mechanism.	Unable to release/retrieve payload.	Part or all of the mission may be aborted. If the failure is such that the payload can neither be securely attached nor completely released from the Tug, then both vehicles may have to be abandoned.
Electrical Power	Loss of Power.	All except during final 30 min before pickup.	Conditioning system, gas lines, case leaks.	Loss of Tug.	No redundancy exists. Tug cannot survive in space for later pickup without power.
	Loss of fuel cell.	During final 30 min especially if near the Orbiter.	Fuel cell failures leading to free hydrogen (e.g., failure of cooling system, gas leaks).	Hazard to Orbiter.	Tug should not be picked up after fuel cell failure unless it is determined to be safe.
Communications	Loss of communications.	All.	Filter, RC multiplexer, hybrid junction.	Unable to dock with payload. Unable to communicate with other STS elements.	Computer could be programmed to return to Orbiter pickup point when it determines communications have failed.
Thermal Control	Loss of temperature control of cryogenic propellant tanks.	All.	Multi-layer insulation damage due to vent valve failure, meteoroid puncture, excessive vibration, etc.	Excessive propellant boiloff.	Excessive propellant boiloff could result in the need for immediate return of the Tug to the Orbiter.

occurs during or after deployment, then the effect could result in the loss of the Tug and perhaps the loss of the Orbiter. Damage to the Tug docking mechanism that prohibits the adequate latching of the Tug inside the Orbiter in preparation for reentry represents perhaps one of the most serious threats to the Orbiter. This is a type of failure that must be detected prior to reentry. If the Tug cannot be secured properly inside the Orbiter bay, it may be necessary to abandon the Tug. Orbiter reentry with a Tug that is free to move inside the Orbiter bay could be disastrous. Therefore, an operational procedure must be developed that will adequately determine the status of the Orbiter/Tug latching mechanism.

Damage to the Tug/payload deployment/retrieval mechanism may prohibit the deployment or retrieval of the payload. This could result from a malfunction of the latching mechanism or from physical damage incurred during payload deployment or retrieval. The effects of this type of failure are not quite as serious as an Orbiter/Tug docking mechanism failure, but it could result in aborting part or all of the mission. If the failure or damage occurred prior to payload deployment, then the Tug/payload would return to the Orbiter; hence, the total mission would be aborted. If the failure occurred subsequent to deployment but prior to or during retrieval, then the retrieval portion of the mission could not be completed. If the failure occurred during retrieval and the failure was such that the payload could neither be secured properly nor released, then the Tug and the payload would have to be abandoned.

Damage to the propellant tank insulation system could result from a failure in the venting and purge system, excessive vibration during ascent, or meteoroid puncture. The effect is dependent on the severity of the damage. If excessive propellant boil-off results, then it may be necessary for the Tug to return immediately to the Orbiter. The time required for the Tug to return to the Orbiter orbit from the trans-synchronous coast orbit is discussed in Section 4.E.4.

(b) Group 2. The Main Propulsion System (MPS) consists of a single engine and thus complete loss of thrust (or major degradation) is possible if the engine or any supporting hardware fails. This includes the two pre-burners, coaxial injector, propellant boost pumps, hot gas driven turbopumps, retractable nozzle, engine control, and fuel lines. In the event of a failure of the MPS, the auxiliary propulsion system (APS) could be used, provided the APS had access to the MPS propellants. The performance capability of the Tug with a failed MPS is discussed in detail in Section 4.E.3.

(c) Group 3. The electrical power subsystem as described in Ref. 5 consists of a single fuel cell augmented with a battery capable of supplying emergency power for 30 minutes. A failure in the fuel cell at any time after the Tug has left the Orbiter parking orbit would result in the loss of the Tug and its payload. Since some fuel cell failures result in the release of free hydrogen, the retrieval of a Tug with a disabled fuel cell (failure occurred within the last 30 minutes of docking) may create a hazard inside the Orbiter bay. Hence, the status of the fuel cell should be known prior to Tug retrieval.

(d) Group 4. Although the communications subsystem is redundant in most areas, it does contain three single thread items. These include the filter, the RF multiplexer, and the hybrid junction. Although the likelihood that any of these devices would fail is low since they are mainly passive, the failure could prevent payload docking due to the loss of TV coverage or the failure could result in the complete loss of Tug communications. The complete loss of communications could result in the loss of the Tug.

(e) Group 5. Failure in attitude control during payload deployment/retrieval or while in the vicinity of the Orbiter could result in damage to any or all three of the elements. Although redundancy exists, any failure must be detected and the redundant element brought on line with sufficient speed to prevent any damage. Orbiter manual override capability of all safety-critical Tug functions while the Tug is in the vicinity of the Orbiter should be considered.

(2) Secondary Failure Modes

The autocollimator constitutes a single string item in the Tug Guidance, Navigation, and Control subsystem. The autocollimator is used to improve navigation accuracy by determining the alignment between the star tracker and horizon sensor mounting bases. The loss of the autocollimator would result in a minor degradation in navigation accuracy rather than a mission abort.

d. Payload Failures

(1) Failure Modes

Table 4-5 is a listing of the failure modes for payloads. For this assessment a knowledge of the specific failures that may occur in the payload is not as important in determining the effects on the remaining STS elements as is the knowledge of specific Tug and Shuttle failures. The only payload failure information necessary for this assessment is that a failure has occurred and that payload deployment or retrieval is possible without creating any hazard to the Tug or Orbiter.

(a) Group 1. Damage to the payload docking system could prevent payload retrieval (failures that prevent payload deployment are discussed under Tug failures). This damage could result from an off-nominal deployment/ retrieval operation or from a collision with a foreign object during the time that the payload has been on orbit. The Tug TV cameras could possibly be used to visually assess the external physical condition of the payload prior to retrieval.

(b) Group 2. The effect on the mission of the failure of a payload to pass checkout is dependent on the mission phase and the type of payload failure that occurred. If the payload failure occurred prior to Tug/payload deployment by the Orbiter, the Orbiter could either return to earth with the Tug/ payload or deploy the Tug/payload if the failure were such that it would create a hazard inside the Orbiter bay during reentry.

Table 4-5. Payload Failure Modes of Concern

Area	Failure Mode	Time Phase	Causes	System Effects	Comments
Checkout	Failed checkout.	Prior to Tug/Payload release from orbiter.	Failure in payload subsystem.	Cannot perform mission.	Orbiter would probably return to the ground if the payload did not pass checkout.
		Prior to payload release from Tug.		Payload may not be able to function on orbit.	The operational procedure followed is dependent on the type of failure. The payload could either be deployed or returned to earth.
		Prior to retrieval by Tug.		Possible hazard to Tug if retrieved.	The Tug may elect not to retrieve payload if the failure is such as to present a hazard to the Tug.
		Prior to retrieval of Tug/payload by Orbiter.		Possible hazard to Orbiter if retrieved.	The Orbiter may not retrieve the payload if it would present a hazard to the Orbiter.
Attitude Control	Premature firing of attitude control engines.	While attached to Tug (includes the time inside Orbiter bay).	Extraneous signals.	Could result in deviation of intended Tug flight trajectory or damage to Orbiter.	The payload attitude control system must be deactivated while attached to the Tug.
	Loss of control.	During retrieval or deployment by Tug.	Intermittent operation, extraneous outputs.	Possible damage to Tug and/or payload.	Payload must be stable during deployment and retrieval by Tug.
Docking System	Improper operation of docking mechanism.	During retrieval or deployment.	Failure or damage to Tug/payload release/ capture mechanism.	Unable to deploy or retrieve payload.	Part of mission may have to be aborted. Tug TV cameras might be used to access physical condition of payload prior to retrieval.

If the payload fails to pass checkout after reaching the mission orbit, the operational procedure is again dependent on the type of payload failure. The Tug may elect to deploy the failed payload and complete the rest of the mission or it may elect to bring back the failed payload. The operational procedure for any payload failure will be dependent on whether or not the failed payload would present a hazard to the Tug or the Orbiter.

(c) Group 5. A failure of the payload attitude control system while the payload is attached to the Tug could result in the loss of or severe damage to all three vehicles, i.e., the Orbiter, the Tug, and the payload. The payload attitude control system should be deactivated while attached to the Tug. The loss of attitude control during payload deployment or retrieval could prevent the successful completion of the operation and/or cause extensive damage to the Tug and payload.

(2) Secondary Failure Modes

Table 4-6 is a listing of the most frequent failures that have occurred on payloads (Ref. 11, 12). Although most of these modes lead to loss or degradation of the payload, they should not interfere with the ability of the Tug to capture it. The status of all safety critical systems should be determined before capture of a payload.

e. Hazards

Some of the hazards that could be created by either the Tug or the payload while they are in or near the Orbiter are listed in Tables 4-7 and 4-8. By incorporating proper design features and operational procedures, the probability of occurrence of these hazards should be reduced to a minimum.

The hazards presented to the Orbiter by the Tug are shown in Table 4-7. Most of these hazards are concerned with the main and auxiliary propulsion systems and were alluded to in the discussion of the possible Tug failure modes.

The payload hazards are shown in Table 4-8.

Table 4-6. Payload Failures in Space (Ref. 11, 12)

Item	Failures/10^6 hr
1. Magnetic Tape Unit	27.0
2. Horizon Sensors	6.1
3. Telemetry Encoders	4.2
4. Vidicon Cameras	3.3
5. Timers and Clocks	2.6
6. Transmitters	1.8
7. Transponders	1.1
8. Computers	1.1
9. Batteries	1.0
10. DC/DC Converters	0.57
11. Command Distribution Units	0.5
12. Motors	0.28
13. Regulators, Voltage	0.26
14. Regulators, Pressure	0.14
15. Receivers	0.12
16. Decoders	0.024
17. Oscillators	0.021

Table 4-7. Tug Hazards (to Orbiter)

Hazard	Orbiter Time Phase	Possible Results	Comments
Improper operation of APS	During Tug deployment/retrieval.	Sudden turn into Orbiter (with resultant damage).	Time involved for fault detection and redundancy switching is important to prevent damage to the Orbiter and Tug vehicles.
Hydrogen Leaks (from propulsion systems and fuel cell)	While Tug is inside payload bay.	Fire, explosion, atmosphere contamination.	Sensors detecting the gas should be required and a plan developed to cover this contingency (e.g., purging Orbiter bay).
Premature Firing of Engine(s)	While Tug is inside payload bay.	Damage to Orbiter.	A safing requirement should be developed for all engines, making sure no failure results in premature engine firing.
Loose Tug in Bay	While Tug is inside payload bay.	Structure and component damage.	One danger is that a "damaged" Tug may be difficult to latch down. Special procedures should be developed or Tug may have to be abandoned.
Engine Plume Effects	When Tug is near Orbiter.	Heat damage to structure.	Tug propulsion systems should not be operated near the Orbiter.

Table 4-8. Payload Hazards (to Orbiter)

Hazard	Orbiter Time Phase	Possible Results	Comments
Loose Parts	While payload is inside bay.	Damage to Orbiter.	Payload should be inspected for damage before it is stored in the Orbiter bay.
Premature Firing of Explosive Devices (including squibs for deployable devices)	Until Tug release (or near the Orbiter).	Structure damage to Orbiter.	A safing procedure similar to that shown for the Tug engines should be followed.
Tank Leakage (hydrogen or other gases and chemicals)	While payload is inside bay.	Possible fire, explosion, atmosphere contamination.	A similar procedure as for the Tug (hydrogen leaks) should be followed.
Radioactive Material (atomic batteries)	While payload is inside bay.	Danger to crew and vehicle contamination.	Procedures should be developed for handling radioactive material.
Other Dangerous Items (e.g., fuel cells, reaction wheels)	While payload is inside bay.	Potential fire, explosion, contamination.	These items should not be activated until a safe distance from the Orbiter. Items should be "safed" and verified before retrieval.

4. STS ABORT EFFECTS AND IMPACTS

In the previous two sections, the effects on the STS elements of a failure in one of the flight elements were assessed. In the following paragraphs, the resultant major effects and impacts either on the design of the elements or on operational procedures are presented. These are summarized in Table 4-9.

a. Orbiter

The impact on the Orbiter of an abort during the ascent phase of the Shuttle flight is dependent on whether or not there is enough time to dump the Tug propellants. For the ascent abort regimes defined in Table 4-1, there is a minimum time of approximately 200 seconds to dump the Tug propellants. A trade study would be required to determine whether the Orbiter should provide for propellant dump, design for the added payload weight, or accept a reduction in the structure safety factors. The impacts on the Tug vehicle would also have to be considered. Also, at the time of the writing of this report, the Shuttle abort capability was in the process of being revised, i.e., the capability for thrust terminating the solid rocket motors was deleted. This should result in a longer minimum time for propellant dump. Until the Shuttle abort capabilities are adequately defined, no definite design impacts can be determined.

The possibility of a failure or damage to the Orbiter-to-Tug latching or tie-down system highlights the need for a procedure to adequately determine the status of this system in preparation for Orbiter reentry. The effect of a loose Tug inside the Orbiter bay during reentry could be catastrophic.

b. Tug

The impact on the Tug of a Shuttle abort during the ascent phase of Shuttle flight is dependent on whether or not there is sufficient time to dump the propellants. The baseline Tug used for this study (Ref. 5) does not have the capability to withstand the loads associated with landing with a full load of propellants. Hence, either the vehicle must be designed to withstand

Table 4-9. STS Abort Effects/Impacts Summary

STS ELEMENT	FAILURE MODE	GROSS EFFECT ON ELEMENT	ELEMENT IMPACT
ORBITER	1. Shuttle propulsion system or solid rocket motor failure during ascent phase.	1. Land with fully or partially fueled Tug.	1. Design for additional payload weight during return/reentry, accept lower safety factors during reentry, or provide for rapid Tug propellant dump.
	2. Damage to Orbiter/Tug docking mechanism.	2. Inability to properly secure Tug inside bay for reentry may be catastrophic.	2. Develop operational procedures to adequately determine the status of the Orbiter/Tug latching mechanism.
TUG	1. Shuttle propulsion system or solid rocket motor failure during ascent phase.	1. Land with full or partially full propellant tanks.	1. Design for structural integrity to land with full propellant tanks or provide for rapid propellant dump.
	2. Tug or payload failure which necessitates Tug return to Orbiter.	2. Determine proper phasing for unscheduled return to Orbiter parking orbit.	2. Tug must be able to do on-board mission planning or have communication with ground control.
	3. Orbiter return to earth without Tug due to Orbiter failure.	3. Remain in low earth parking orbit for extended time for retrieval by subsequent Orbiter flight.	3. Tug would have to survive extended on-orbit stay time. Baseline design limited in respect to on-orbit stay capability.
	4. Tug electrical power failure.	4. Loss of Tug vehicle.	4. Baseline design has single fuel cell. Add a redundant fuel cell to reduce this risk.
	5. Tug electrical power failure just prior to retrieval by Orbiter (due to H_2 leak).	5. Creates possible hazard inside Orbiter bay due to possible H_2 leak, if Tug is retrieved.	5. Operational procedure needed to determine fuel cell status prior to retrieval.
	6. Failure in Tug main propulsion system.	6. Perform mission or abort without main engine thrust.	6. Tug could return to Orbiter using the auxiliary propulsion system (APS) if the APS had access to the main engine propellants. Baseline design does not have this feature.
	7. Failure of Tug propellant tank insulation system.	7. Excessive propellant boil-off.	7. Excessive propellant boil-off would require that the Tug return immediately to the Orbiter for retrieval.
PAYLOAD	1. Tug failure which necessitates jettisoning the payload and returning to Orbiter.	1. Deployed in off-nominal orbit.	1. Payload would remain in off-nominal orbit until retrieval by a subsequent Tug flight.
GROUND	1. Shuttle failure during ascent phase which requires immediate return to launch site.	1. Tug returned with full or partially full propellant tanks.	1. Ground servicing equipment and operations must provide for horizontal Tug propellant drain.
	2. Failure in STS flight elements which requires early return of elements.	2. Altered flow of flight elements through ground turnaround cycle.	2. The early return of the flight elements may tax the capabilities of the ground facilities.
	3. Failure in any of the flight elements which necessitates an abort action.	3. Communication with the flight elements may be necessary to assist in abort procedures.	3. The ground may be required to provide executive confirmation and real time mission planning in abort situations.

these loads or be designed to rapidly dump the propellants. The relative merits of either option should be the subject of a trade study. The time available for dumping is dependent on the abort trajectory of the Shuttle. As mentioned previously, the Shuttle abort capability was in the process of being revised at the time of the writing of this report.

The impact on the Tug of a failure in either the Tug or payload which requires the Tug to return immediately to the Orbiter is dependent on the philosophy used in abort management and control. All important abort decisions and related necessary real time mission planning could be done on the ground. In this case, the main requirement on the Tug would be that it have communication with ground control. On the other hand, if the abort actions were to be totally autonomous, then the impact on the flight vehicle could be significant. The subject of vehicle requirements for autonomous abort capability is discussed in Section 4. F.

In the event of an Orbiter failure which necessitates the early return of the Orbiter prior to Tug retrieval, the Tug may be required to remain on orbit longer than anticipated. If the failure occurred just prior to Tug retrieval and the Orbiter required two weeks to be refurbished and processed through the ground turnaround cycle, then the Tug would have to stay on orbit an additional two weeks if no other Orbiter were available. The baseline Tug (Ref. 5) has approximately seven days on-orbit capability. Hence, some of the Tug systems, e.g., electrical power and propellant supply for attitude control, would require additional capability to survive the added time on orbit. The degree to which this added capability should be incorporated and the resultant impact on the Tug design should be the subject of a study.

The Tug electrical power system consists of a single fuel cell and a backup battery for 30 minutes of emergency power. In the event of a fuel cell failure when the Tug is away from the Orbiter, the Tug and its payload would be lost. This impact of a single fuel cell failure could be eliminated by the addition of a redundant fuel cell. If a fuel cell failure occurred during the final 30 minutes of docking with the Orbiter, then the emergency battery

could provide the necessary electrical power. However, certain types of fuel cell failures result in the release of free hydrogen which could create a hazard inside the Orbiter bay. Therefore, a procedure is required for determining the status of the fuel cell prior to retrieval.

The Tug main propulsion system consists of a single main engine; therefore, a single failure could result in a degraded or complete loss of main engine thrust. In the event of a main engine failure, the auxiliary propulsion system (APS) could be used to provide thrust at a reduced level if the APS had access to the main propellants. The performance capability of the Tug for this mode of operation is discussed in Section 4.E. For the baseline Tug (Ref. 5) used in this study, the APS does not have access to the main engine propellants. To provide for a backup capability in the event of main engine failure, it is recommended that the propulsion system design allow for access of the APS to the main propellants.

A failure in the propellant tank insulation system which resulted in excessive propellant boil-off could shorten the on-orbit life of the Tug considerably. The actual effect, of course, is dependent on the severity of the insulation damage. It could be necessary for the Tug to return to the Orbiter as quickly as possible. The time required for the Tug to return to the Orbiter from the trans-synchronous coast orbit is presented in Section 4.E.

c. Payload

The main impact on the payload derived from the abort assessment is the result of a Tug failure which requires the Tug to jettison the payload in an off-nominal orbit. Hence, the payload would have to survive in this orbit until retrieval by a subsequent Tug flight. The impact on the payload is a function of the difference between the design orbit and the off-nominal orbit, i.e., if the payload was designed to operate at synchronous altitude and instead the payload was deployed in a low earth orbit, the difference in the heat input from the earth's albedo and the sun may result in damage to the payload. Whether or not the payload should be designed to account for

the possibility of an off-nominal orbit insertion should be the subject of a trade study for each individual payload which would address the probability of this occurrence and the impact on the payload design.

d. Ground

The impact on the ground facilities of an early abort of the Orbiter and Tug is that the ground safing area must have the capability of safing a Tug that still contains a significant amount of propellants. The amount of propellants that must be purged from the Tug will be dependent on the decision as to whether or not the Tug propellants will be dumped before landing.

Another impact on the ground facilities of an early abort is the possible taxing of the physical capacity of the ground turnaround facilities to handle additional flight elements. The ground turnaround timelines and facilities must be flexible enough to account for an occasional perturbation in the scheduled flow of flight elements through the turnaround cycle.

In the event of an abort situation, the ground may be required to provide executive decisions and real time mission planning. This would require adequate communications between the ground and the flight elements at all times. The impact on the ground flight control is dependent on the philosophy used in abort planning.

E. TUG ABORT PERFORMANCE CAPABILITY

1. INTRODUCTION

The performance capability of the Tug was analyzed for two abort conditions: (1) performance with loss of or degraded main engine thrust; and (2) minimum time required for return to the Orbiter parking orbit.

The mission used for this analysis was the baseline geosynchronous payload replacement mission defined previously. The nominal Tug mission consists of the following six maneuvers:

a. The first burn, which begins in a 296 x 296 km (160 x 160 nmi), 28.5 deg inclined orbit, injects the Tug into a transfer orbit with apogee at synchronous altitude and accomplishes a plane change of 2 deg.

b. The second burn circularizes the orbit at synchronous altitude and completes the remaining 26.5 deg plane change to produce a synchronous equatorial orbit.

c. After deploying the first payload, the Space Tug performs a third burn (actually a series of burns) to accomplish on-orbit phasing and retrieve a second payload.

d. With the second payload attached, a deorbit burn is performed to lower the Tug's perigee altitude to 315 km (170 nmi) and increase inclination to 26.5 deg.

e. As the Tug approaches perigee a fifth burn is executed to produce a 315 x 719 km (170 x 388 nmi) phasing orbit with an inclination of 28.5 deg.

f. The sixth burn circularizes the Tug orbit at 315 km (170 nmi).

A schematic of the nominal mission is shown in Fig. 4-4.

Loss of the nominal Tug thrust level of 44,482 N (10,000 lb) was assumed to occur prior to any one of the six burns. Failure modes considered were: (1) only the main engine idle mode thrust of 4448 N (1000 lb) was available; and (2) only the Reaction Control System (RCS) thrust of 534 N (120 lb) was available.

In both failure modes all nominal propellant and reserve fuel were used for thrust. The lower specific impulse (I_{sp}) which accompanies these failure modes, however, reduces the amount of ΔV which can be obtained from these propellants. In addition, the lower thrust-to-weight ratios cause an increase in gravity or turning losses during the burns so that a higher than nominal ΔV must be expended to accomplish the nominal maneuvers. These two factors act against the Tug in such a degraded thrust abort condition. Table 4-10 shows the I_{sp} values for nominal and degraded thrust levels. Figure 4-5 shows the ΔV above the impulsive solution which is required to attain an apogee at synchronous altitude, as a function of thrust level. Clearly the gravity losses for low altitude burns with either the 4448 N (1000 lb) or the 534 N (120 lb) thrust are significant.

For each of the twelve abort conditions, viz., failure to either the idle mode or RCS prior to any of the six burns, the following questions were addressed:

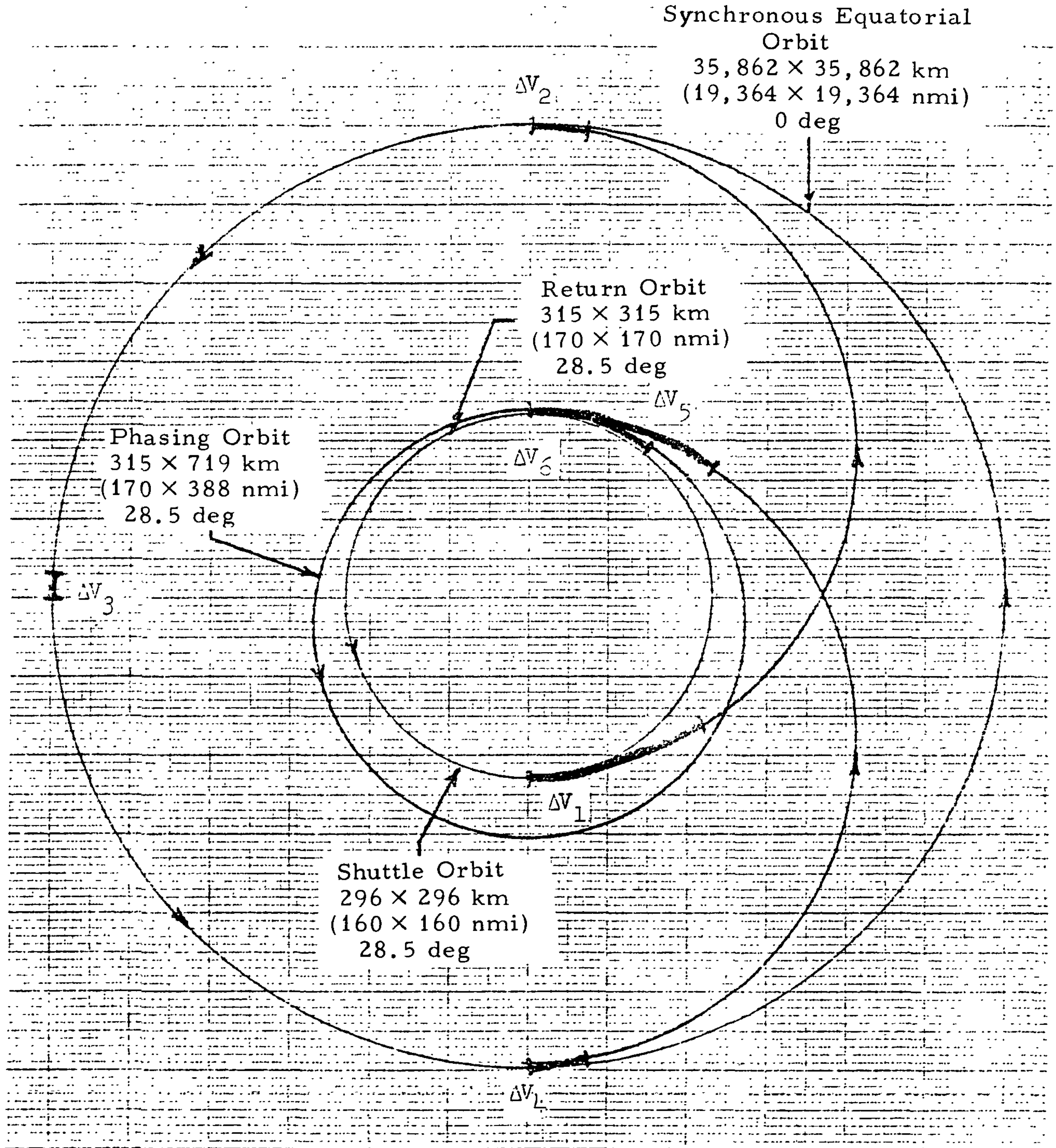


Figure 4-4. Nominal Space Tug Geosynchronous Mission

Table 4-10. Thrust Levels and I_{sp} Values for Nominal and Abort Engine Modes

Mode	Thrust Level N	Thrust Level (lb)	I_{sp} (sec)
Nominal Main Engine	44,482	(10,000)	470
Main Engine Idle Mode	4,448	(1,000)	460
Reaction Control System (RCS)	534	(120)	380

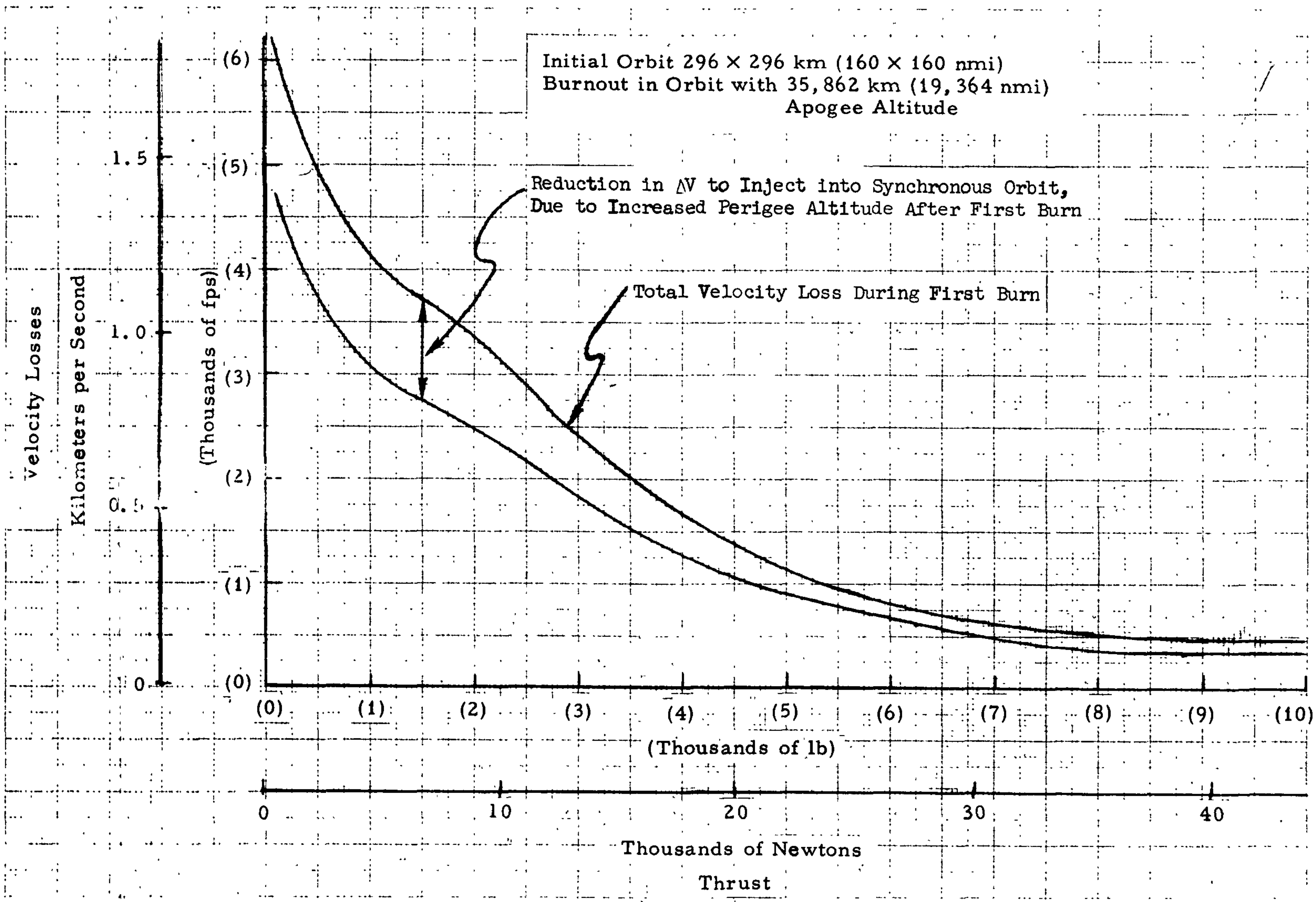


Figure 4-5. Effect of Thrust on Velocity Losses

a. Can the baseline mission be completed? (Replacement)

b. Can a deployment-only mission be completed? (Deploy only)

c. Can the Tug/payload return to the Orbiter (intact abort)? If not, to what orbit can the Tug/payload return?

d. Can the Tug, having jettisoned the payload in the orbit existing at the time of failure, return to the Orbiter? (Jettison abort)

For the minimum return time portion of the analysis, the Tug was assumed to have completed the first burn and injected into the transfer orbit. At some point during the ascent transfer it was assumed necessary to return the Tug and its payload in as short a time as practicable to a low earth orbit from which it may be retrieved by the Orbiter.

2. TUG PERFORMANCE BASELINE

The performance baseline, which is derived from data in Ref. 5, is shown in Table 4-11. Several differences between Table 4-11 and Ref. 5 will be noted. In Ref. 5, the usable or impulse propellant is listed as 24,306 kg (53,585 lb) while the non-impulse propellant (RCS, start/stop losses, vented propellants, and fuel cell reactants) total up to 354 kg (780 lb). An effective I_{sp} is computed in Table 4-11 by multiplying the rated I_{sp} by the ratio of impulse propellant to total propellant used. Using this effective I_{sp}, the 24,306 kg (53,585 lb) of impulse propellant, and a 1361 kg (3000 lb) payload, it was found that, after the nominal mission, 123 kg (271 lb) of fuel remained in the tanks. This represents a contingency factor in the Tug design study. In order to maintain a conservative viewpoint in the present abort analysis, this extra 123 kg (271 lb) has been added to the category of payload weight and subtracted from the usable impulse propellant weight. Thus the figures of 1484 kg (3271 lb) for payload weight and 24, 183 kg (53, 314 lb) for impulse propellants are arrived at in Table 4-11. Burnout weight was also adjusted accordingly. For an effective I_{sp} of 463.3 seconds, an initial weight of 28, 820 kg (63, 538 lb), and a

Table 4-11. Space Tug Baseline

Ignition Weight	28,820 kg	(63,538 lb)
Impulse Propellants (main + OMS)	24,183 kg	(53,314 lb)
Non-Impulse Expendables	354 kg	(780 lb)
Burnout Weight	4,284 (4,125[1]) kg	[9,444 (9,094[1]) lb]
Tug Inert Weight	2,800 (2,641[1]) kg	[6,173 (5,823[1]) lb]
Payload (round-trip)	1,484 kg	(3,271 lb)

Effective I_{sp} Calculation

$$I_{sp}\text{ (effective)} = I_{sp}\text{ (rated)} \times \left(\frac{\text{Impulse Propellant}}{\text{Impulse + Non-Impulse Propellant}}\right)$$

Mode	Rated I_{sp} (sec)	Effective I_{sp} (sec)
Nominal Main Engine	470 470	463.3 463.3
Main Engine Idle Mode	460	453
Reaction Control System (RCS)	380	374.5

[1]Does not include 159 kg (350 lb) of main engine fuel reserves.

nominal mission ΔV of 8660 mps (28,411 fps), the burnout weight of 4284 kg (9444 lb) is obtained. Furthermore, if the 159 kg (350 lb) of main engine reserve propellant is allowed to be expended, the burnout and Tug inert weights are decreased by 159 kg (350 lb) (see footnoted figures in Table 4-11), and the ΔV available is raised to 8831 mps (28,973 fps), which is exactly the requirement for the nominal plus contingency mission as detailed in Table 5 of Ref. 5. For the purpose of this study it is assumed that the 159 kg (350 lb) reserve propellant is available for thrust in the event of an abort situation.

3. DEGRADED THRUST

a. Method of Analysis

Twelve different abort situations were studied (failure to either the idle mode or RCS prior to any of the six burns). For each of these situations the four questions discussed earlier were answered. The first step in the analysis was to determine the nominal amount of fuel remaining at the time of the assumed failure and the amount of ΔV which was available from this fuel under the degraded I_{sp} conditions. This amount of ΔV depended upon the type of mission which was to be attempted (i.e., deployment only, complete replacement, or payload jettison).

The next step was to determine the ΔV required to perform the desired orbital transfers. In this connection the Aerospace Modularized Vehicle Simulation (MVS) program was used. The MVS accurately simulates vehicle maneuvers including gravity losses and provides a pseudo-optimal steering profile for the mission utilizing an iterative cost function minimization scheme. The control arrived at was only pseudo-optimal in that constraints on the form of the control were assumed in order to allow convergence of the optimization. During burning the thrust vector orientation was specified by the in-plane thrust angle α and the out-of-plane thrust angle β defined in Fig. 4-6. Angle β controls the amount of inclination change accomplished during a burning period. It was assumed to be a constant

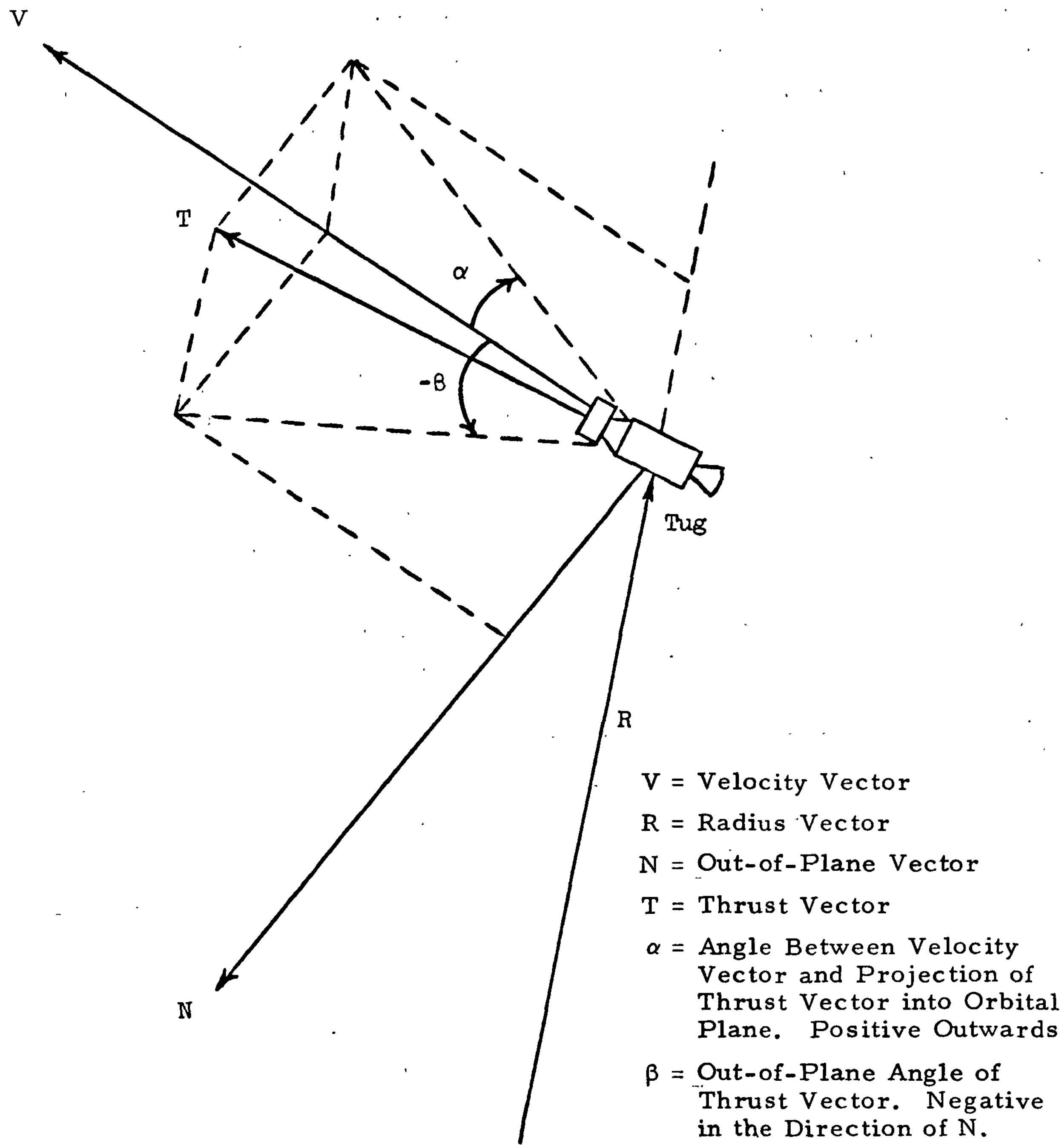


Figure 4-6. Definition of Thrust Angles

value for each of the burns except that its sign was reversed at the antinodes to maintain the inclination change in the proper direction. The in-plane thrust angle α was assumed to be a linear function of either time, flight path angle γ, or mean anomaly for each burn. MVS iteratively seeks α and β for each burn, subject to the above constraints on their form, and the start and stop times of the burns for which the overall required ΔV is a minimum. For long constant thrust trajectories using the RCS thrusters, the MVS program is not well suited and does not provide convergence. For these cases, the trajectories were run on an optimal low thrust trajectory generation program by Mr. T. Edelbaum at the MIT Draper Lab. The only assumption inherent in this program is that continuous thrust is used to effect the transfer of interest.

Having thus determined the ΔV required to perform maneuvers, the ΔV available under reduced thrust at that point in the nominal mission will dictate whether a given mission can be performed. If an abort maneuver could not be completed due to lack of fuel, the orbit existing at the time of fuel exhaustion was determined from simulation printout.

b. Typical Low-Thrust Trajectories

Before the detailed results of the study are presented, it would be desirable to establish a feel for the types of trajectories which can be performed using nominal, idle mode, and RCS thrust. Accordingly, examples of each are presented below. A nominal 44,482 N (10,000 lb) thrust return from synchronous equatorial orbit is pictured in Fig. 4-7. The thrusting arcs are shown as heavy lines and the burn times and ΔVs are given. Although radial distances on the figure have been distorted for presentation purposes, the angular displacements are accurately depicted. Information for this figure was taken from Ref. 5.

The same return executed under idle mode 4448 N (1000 lb) thrust is pictured in Fig. 4-8. Note that burn arcs and burn times are much longer due to the lower thrust-to-weight ratio. (In all low-thrust trajectories run

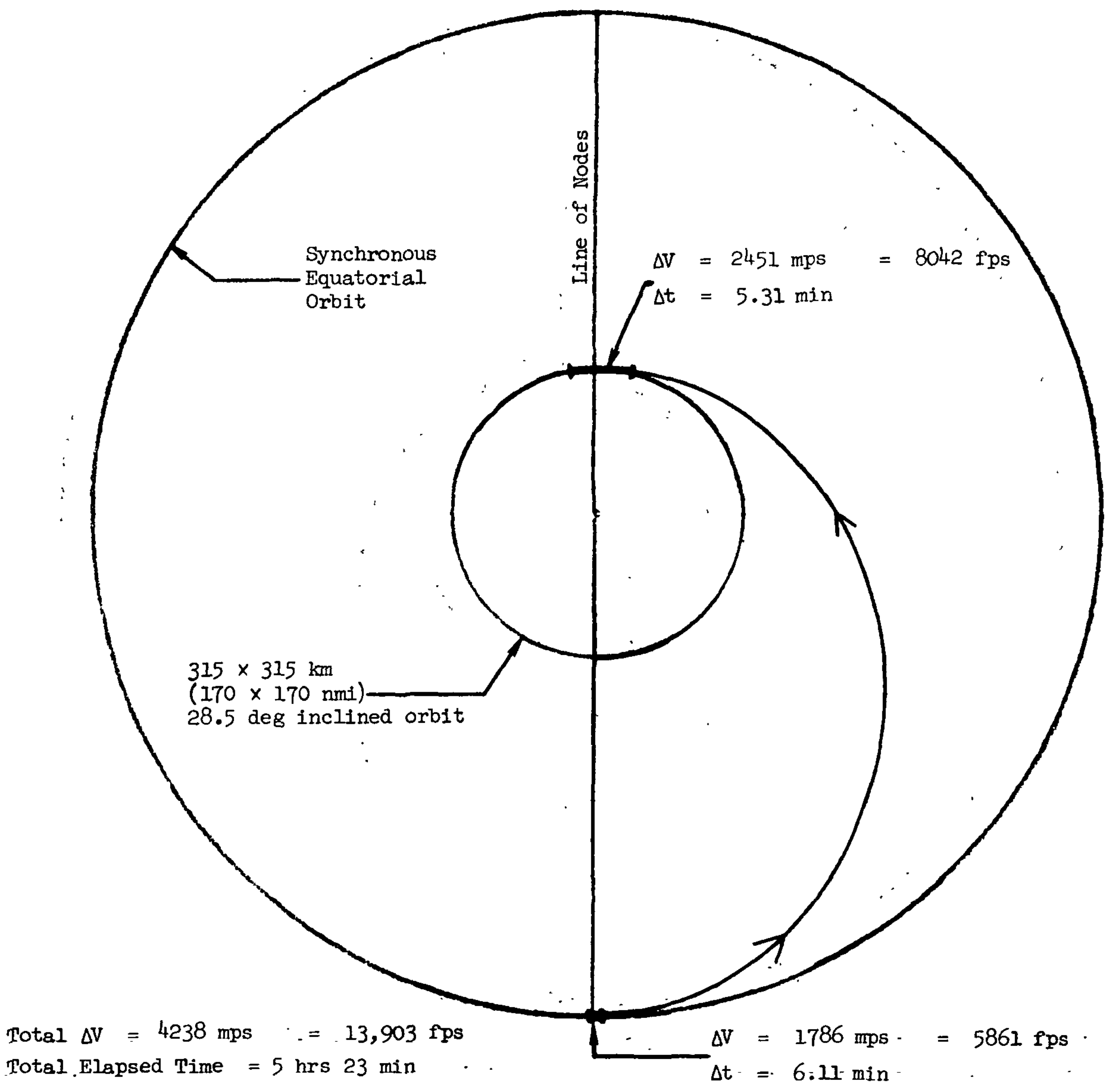


Figure 4-7. Return Trajectory from Geosynchronous Orbit Using Nominal 44,482 N (10,000 lb) Thrust

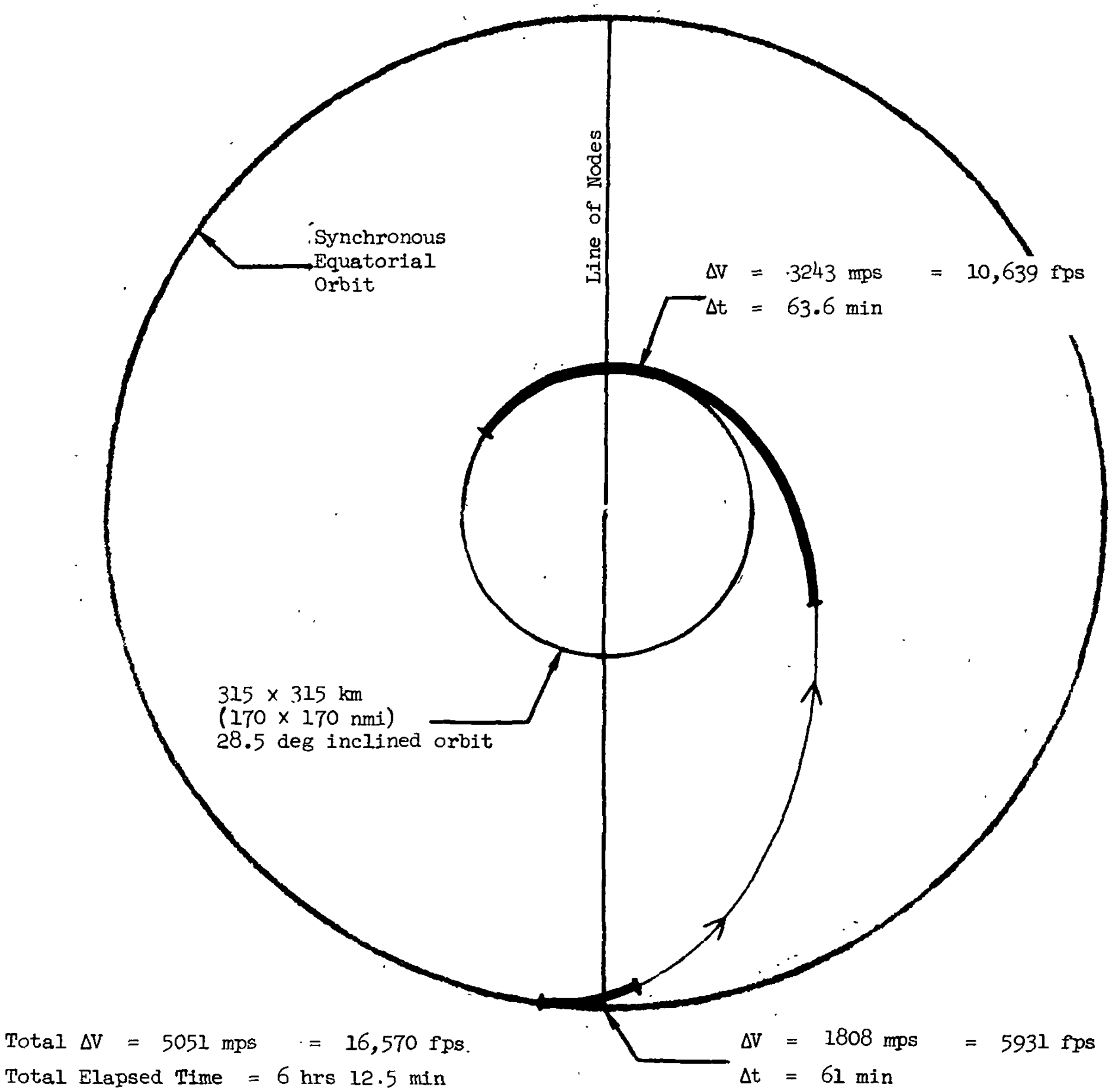


Figure 4-8. Return Trajectory from Geosynchronous Orbit Using Idle Mode 4448 N (1,000 lb) Thrust

for this study the initial vehicle weight is assumed to be the nominal vehicle weight at that particular point in the reference mission.) Table 4-12 contains the trajectory and steering characteristics for this idle mode trajectory as resulting from the MVS simulation and optimization process. The initial geosynchronous equatorial orbit was 35,862 km (19,364 nmi). The first burn (labeled 1A for first apogee burn) of 1808 mps (5931 fps) injected the Tug into a 315 x 35,710 km (170 x 19,282 nmi), 26.5 deg inclined orbit. The second burn (first perigee burn, 1P) of 3243 mps (10,639 fps) circularized the Tug at 315 km (170 nmi) and increased the orbital inclination to 28.5 deg. The burn times Δt and true anomaly subtended during the burns Δf are also provided for each burn.

The optimized values of the steering angles α and β during the burns are supplied in the table. In this case since the first burn was at high altitude and did not subtend a large arc, the in-plane steering angle α for the first burn was chosen to be zero in order to reduce the number of variables and hasten convergence of the optimization procedure. An in-plane control angle α of zero deg was very nearly optimal in cases such as this. An out-of-plane steering angle of $\beta = 35.48$ deg for the first burn produces the 26.5 deg initial plane change. This manner of splitting the overall 28.5 deg of plane change was optimal using impulsive thrust and was found to be optimal as well for the low-thrust trajectories of this study, by comparison to low-thrust trajectories with other plane splits.

The steering angles during the second burn were optimized using the MVS program. The in-plane angle α was assumed to be a linear function of flight path angle γ and was optimized as such. The out-of-plane thrust angle β was assumed to be of constant magnitude and with a sign which changed at each crossing of the antinodes. The antinodes are contained in the plane perpendicular to the line of nodes shown in Fig. 4-8. To maintain the inclination change in the correct direction, the sign of β must be changed each time the vehicle passes through this plane (i.e., at 90 deg from the

Table 4-12. Trajectory Characteristics for Return from Geosynchronous Orbit Using Idle Mode 4448 N (1000 lb) Thrust

Orbit Characteristics			Burn Characteristics[1]			
Apogee Altitude km (nmi)	Perigee Altitude km (nmi)	Inclination deg	No.	ΔV mps (fps)	Δt sec	Δf deg
35,862 (19,364)	35,962 (19,364)	0	1A	1808 (5931)	3660	11.6
35,710 (19,282)	315 (170)	26.5	1P[2]	3243 (10,639)	3760	170
315 (170)	315 (170)	28.5				

Total ΔV = 5051 mps (16,570 fps) Total transfer time = 6 hrs 12 min 29 sec

Steering scheme:

Apogee burn: $\alpha = 0$ deg, $\beta = 35.48$ deg (optimized constant)

Perigee: $\alpha = k \frac{2}{\pi}$, $k = 112.5$ (optimized constant), $\beta = \pm 9.05$ deg (sign changes at the antinodes) (optimized constant)

Notes

[1]No. = burn identification, e.g., 1P is the first perigee burn.

ΔV = delta velocity applied during the burn.

Δt = duration of burn.

Δf = true anomaly subtended during the burn.

[2]In traversing the above trajectory in an Intact Abort situation, the Space Tug fuel is depleted during the course of the perigee burn, leaving the Tug in a 315 × 2037 km (170 × 1100 nmi), 28.5 deg inclined orbit.

ascending or descending node). Thus in the trajectory of Fig. 4-8, the initial value of β during the second burn was $\beta = 9.05$ deg, switching to $\beta = -9.05$ deg at a point 90 deg from the line of nodes.

Altitude versus time for the return from synchronous equatorial orbit to low earth orbit performed using only the RCS thrusters is tabulated in Table 4-13. Here it was assumed that the thrusters are constantly burning, so that the minimum fuel trajectory was also a minimum time trajectory. This trajectory is of spiral form which is typical of constant low-thrust trajectories. For the RCS thrust level, the Tug circles the earth roughly six times before reaching low earth orbit. The altitude and time are recorded for each half revolution in Table 4-13.

The gravity losses experienced under abort thrust conditions can be reduced significantly by the use of multiple burns. For the idle mode thrust return trajectory of Fig. 4-8 this would involve splitting the large perigee burn into two parts. The resulting trajectory is shown in Fig. 4-9 and offers a 151 mps (495 fps) ΔV savings over the single perigee burn return.

A similar multiple burn strategy can be adopted for the case where only RCS thrust is available. As an example, consider the case in which a failure to the RCS thrusters occurs prior to burn 5, at which time the Tug is in the return transfer orbit. With a constant thrusting of the RCS, a ΔV of 5334 mps (17,500 fps) is required to perform the circularization. If, instead, a sequence of 11 perigee burns and 10 apogee burns as pictured in Fig. 4-10 are performed, the necessary ΔV is reduced to 3384 mps (11,102 fps). This represents a savings of 1950 mps (6398 fps). The associated increase in transfer time is not so large as to cause the Tug to exceed its six-day total mission time. The trajectory and steering characteristics for the multiple RCS burn mission of Fig. 4-10 are shown in Table 4-14 using the same format as discussed earlier for Table 4-12. Note that apogee burns add a small amount of ΔV in a posigrade direction so as to raise the perigee altitude to 315 km (170 nmi).

Table 4-13. Return from Geosynchronous Orbit with Continuous RCS Thrust

Rev.	Altitude km	(nmi)	Time (hr)
0	35,862	(19,364)	0
0.5	14,816	(8000)	7.81
1.0	8334	(4500)	11.13
1.5	5741	(3100)	13.28
2.0	4260	(2300)	14.96
2.5	3334	(1800)	16.38
3.0	2593	(1400)	17.62
3.5	2037	(1100)	18.75
4.0	1574	(850)	19.77
4.5	1111	(600)	20.71
5.0	741	(400)	21.57
5.5	519	(280)	22.38
6.0	315	(170)	23.15

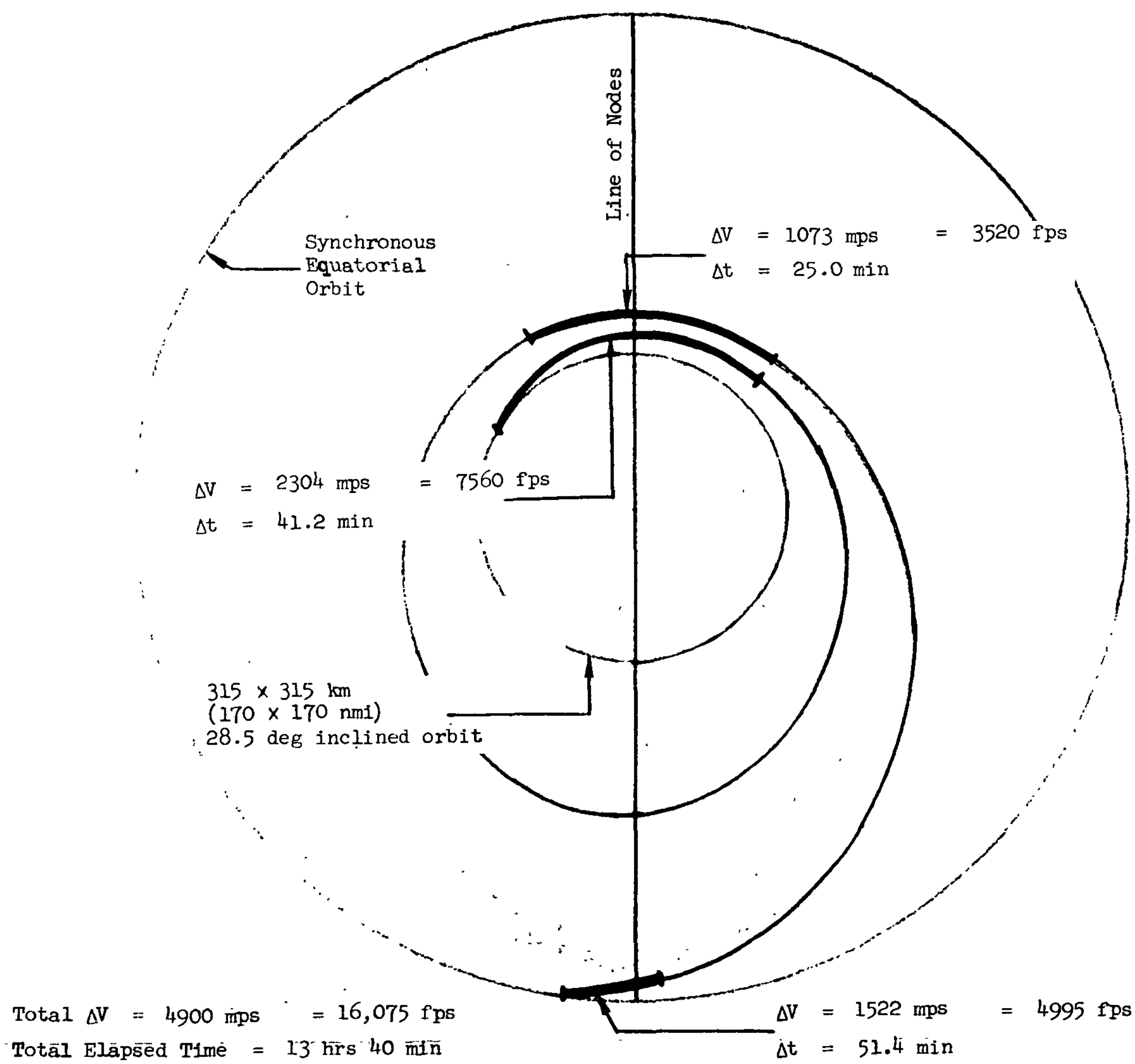
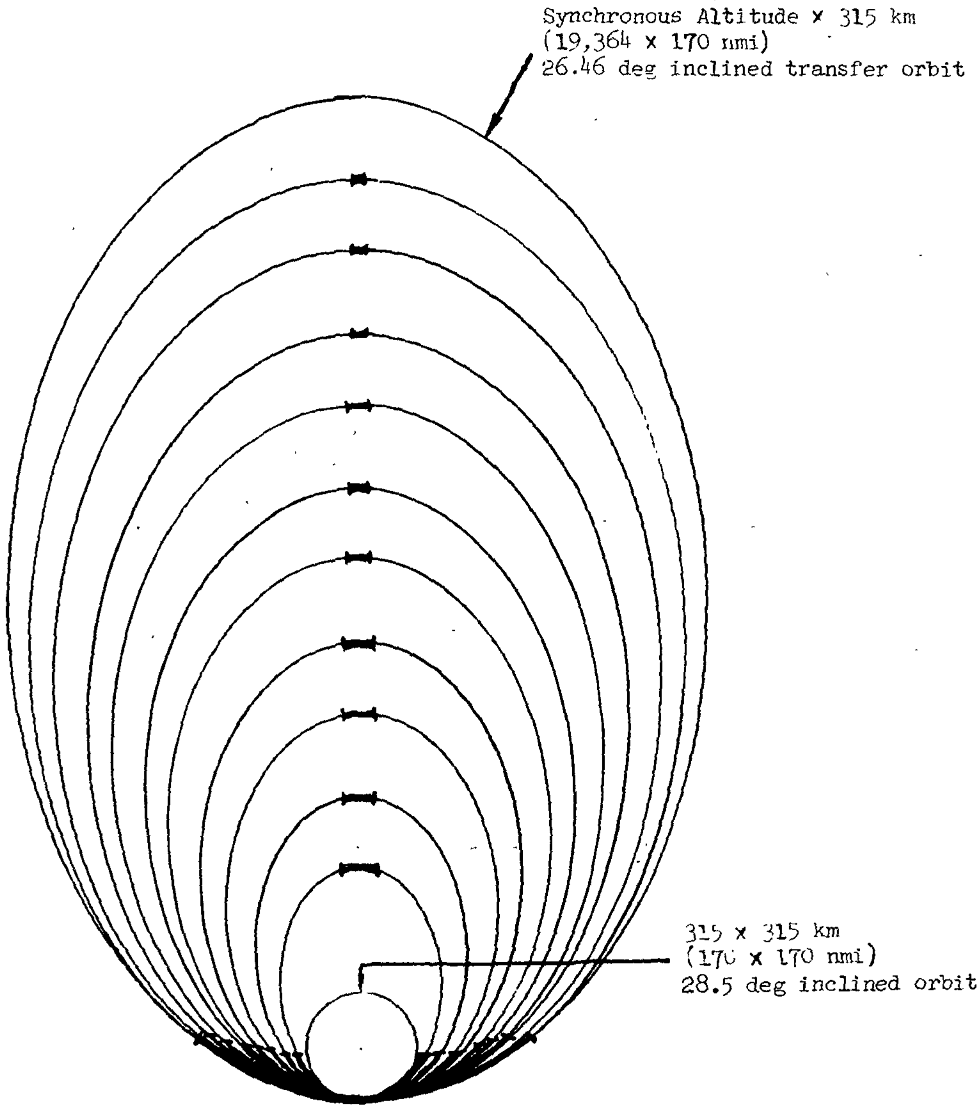


Figure 4-9. Double Perigee Burn Return Trajectory from Geosynchronous Orbit Using Idle Mode



Total ΔV = 3384 mps (11,102 fps)

Total elapsed time = 1 day 15 hrs 16 min

Figure 4-10. Multiple Burn Strategy for Circularization from Descent Transfer Orbit

Table 4-14. Trajectory Characteristics for Circularization from Descent Transfer Orbit using RCS 534 N (120 lb) Thrust

Orbit Characteristics			Burn Characteristics[1]			
Apogee Altitude km (nmi)	Perigee Altitude km (nmi)	Inclination deg	No.	ΔV mps (fps)	Δt sec	Δf deg
35,860 (19,363)	315 (170)	26.46	1P	3048 (1000)	4042	202.0
25,341 (13,683)	183 (99)	26.63	1A	17 (56)	215	0.8
25,341 (13,683)	315 (170)	26.63	2P	3048 (1000)	3703	197.0
18,553 (10,018)	200 (108)	26.79	2A	18 (58)	204	1.2
18,553 (10,018)	315 (170)	26.79	3P	3048 (1000)	3391	192.0
13,807 (7455)	209 (113)	26.95	3A	19 (61)	197	1.8
13,807 (7455)	315 (170)	26.95	4P	3048 (1000)	3106	185.0
10,301 (5562)	215 (116)	27.13	4A	20 (65)	192	2.4
10,301 (5562)	315 (170)	27.13	5P	3048 (1000)	2843	175.0
7614 (4111)	217 (117)	27.32	5A	21 (70)	189	3.2
7614 (4111)	315 (170)	27.32	6P	3048 (1000)	2601	163.0
5497 (2968)	218 (118)	27.54	6A	23 (74)	185	4.3
5497 (2968)	315 (170)	27.54	7P[2]	3048 (1000)	2379	148.0
3800 (2052)	220 (119)	27.78	7A	24 (78)	177	5.5
3800 (2052)	315 (170)	27.78	8P	3048 (1000)	2176	130.0
2432 (1313)	222 (120)	28.05	8A	25 (81)	167	6.5
2432 (1313)	315 (170)	28.05	9P	3048 (1000)	1989	107.0

Table 4-14. Trajectory Characteristics for Circularization from Descent Transfer Orbit using RCS 534 N (120 lb) Thrust (Concluded)

Orbit Characteristics					Burn Characteristics[1]			
Apogee Altitude km	(nmi)	Perigee Altitude km (nmi)	Inclination deg	No.	ΔV mps	(fps)	Δt sec	Δf deg
1335	(721)	224 (121)	28.33					
				9A	25	(83)	157	7.7
1335	(721)	315 (170)	28.33					
				10P	3048	(1000)	1818	53.0
493	(266)	213 (115)	28.60					
				10A	29	(96)	168	8.7
493	(266)	315 (170)	28.60					
				11P	116	(380)	690	104.0
314	(170)	315 (170)	28.60					

Total ΔV = 3384 mps (11,102 fps)

Total Transfer time = 1 day 15 hrs 16 min from apogee
1 day 10 hrs 20 min from perigee

Steering:

Apogee burns: $\alpha = 0$ deg, $\beta = 0$ deg

Perigee burns (except 11P): $\alpha = k$ (mean anomaly) $+ \alpha_o$, $k = 1.016$ (optimized constant), $\alpha_o = -9.533$ deg (optimized constant), $\beta = \pm 9.919$ deg (optimized constant) (sign change at the antinodes)

Final perigee burn (11P): α = near tangential, $\beta = 0$

NOTES:

[1] No. = burn identification, e.g., 1P is the first perigee burn

ΔV = delta velocity applied during the burn

Δt = duration of burn

Δf = true anomaly subtended during the burn

[2] In traversing the above trajectory in an Intact Abort situation, the Space Tug fuel is depleted during burn 7P, leaving the Tug in a 4,445 × 222 km (2400 × 120 nmi), 27.7 deg inclined orbit.

c. Results

Results of the analysis in the form of graphs of ΔV available and ΔV required to perform the complete replacement, deploy-only, intact abort, and jettison abort missions are shown in Figs. 4-11 through 4-14 for both the idle mode thrust and RCS thrust cases.

Figure 4-11 shows the capability to perform either a complete replacement or a deploy-only mission using the idle mode thrust. The horizontal axis of this graph is the Main Propulsion System (MPS) cumulative burn time at the instant of nominal thrust failure. Since the orbital energy and the fuel available vary only during thrusting periods, the required and available ΔV at any point in the mission will be a continuous function of the total thrust time.

As an example in the use of this graph, consider the case where the main engine fails to the idle mode after 25 minutes of accumulated thrusting (i.e., the first transfer orbit insertion, burn 1, has been performed and the failure occurs midway through the mission orbit insertion burn, burn 2). From Fig. 4-11, after 25 minutes of MPS burn time a ΔV of about 5974 mps (19,600 fps) is required to perform either the complete replacement or the deploy-only mission. (Actually the deploy-only mission requires slightly less ΔV than the complete replacement mission due to a higher thrust-to-weight ratio when the payload is not attached. The difference, however, is so small as to be unnoticeable on this graph). The ΔV available from remaining fuel under the reduced I_{sp} condition is about 6980 mps (22,900 fps) for a deploy-only mission and 5486 mps (18,000 fps) for a complete replacement mission. Thus if a failure to idle mode thrust occurs after 25 minutes of accumulated nominal main engine operation a deploy-only mission may be accomplished, whereas a complete replacement mission may not. In fact, the graph indicates that a deploy-only mission is always an achievable alternative under idle mode thrust (assuming the failure occurs prior to the deorbit burn since after this time the deploy-only mission is not defined)

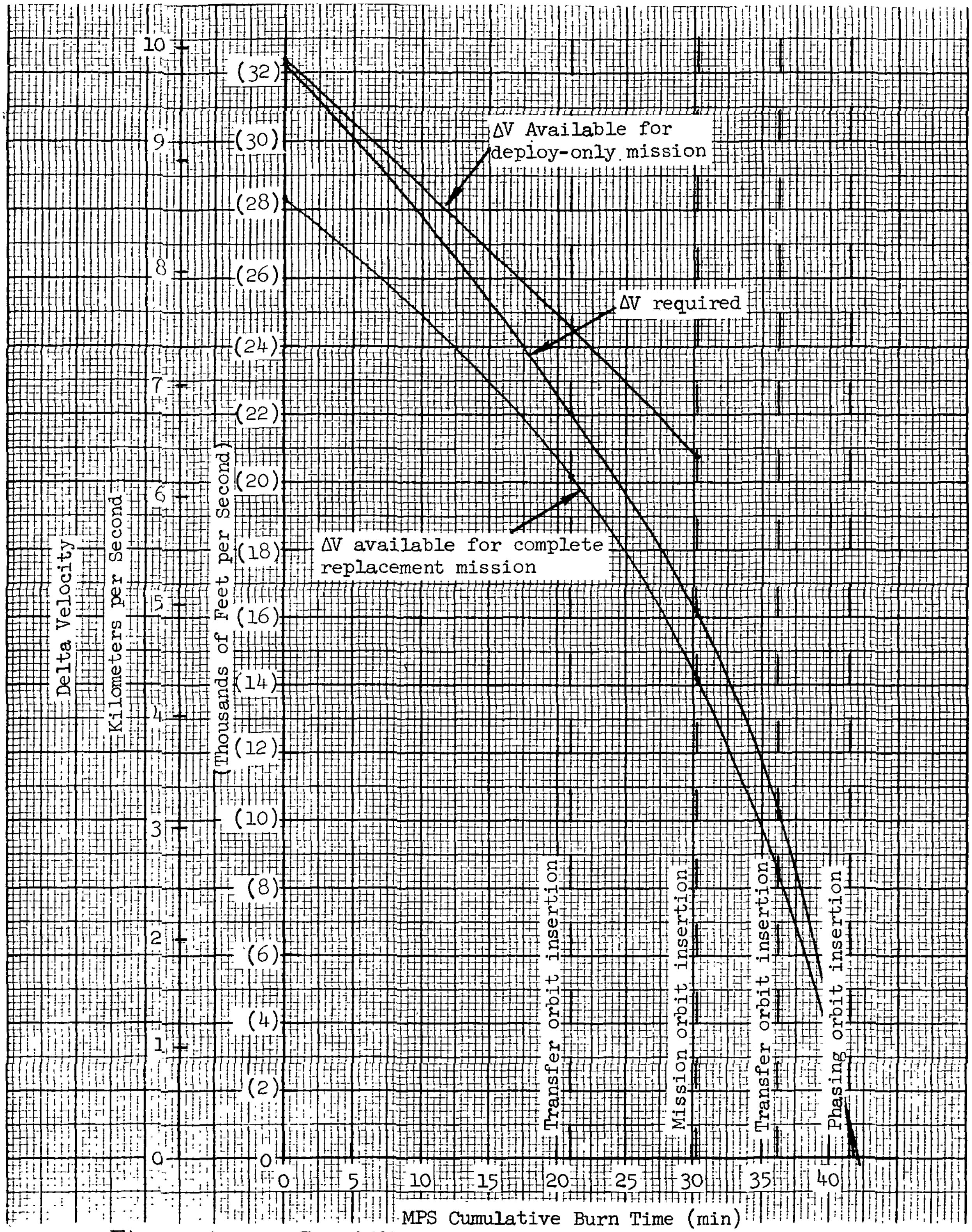


Figure 4-11. Capability to Perform Complete Replacement or Deploy-Only Mission Using Idle Mode Thrust

while the complete replacement mission cannot be performed unless the failure occurs very late in the mission (after about 41 minutes of MPS thrust time has been accumulated). It should be noted that the required ΔV plotted in Fig. 4-11 is based upon trajectories which utilize the double perigee burn scheme discussed earlier for both ascent and descent transfers. In addition to reducing the gravity losses for these low-thrust trajectories, the double perigee burn scheme provides an intermediate coasting orbit which may be utilized for longitude phasing purposes. The reduction in the required ΔV offered by the double perigee burn scheme as compared to the single perigee burn transfer will be shown in the following discussion.

The abort capability of the Space Tug under idle mode thrust conditions is shown in Fig. 4-12. The ΔVs available from the fuel under idle mode I_{sp} conditions for the case where the Tug and attached payload are both returned to the Orbiter (intact abort) and the case where the payload is jettisoned in the orbit existing at the time of the failure and only the Tug is returned to the Orbiter (jettison abort) are plotted against MPS cumulative burn time. Also plotted is the ΔV required to return to the Orbiter using either a single or double perigee burn transfer. The double perigee burn scheme is seen to offer roughly a 151 mps (495 fps) savings for a return from synchronous equatorial orbit.

From Fig. 4-12 it is clear that an idle mode jettison abort can always be accomplished. An intact abort using idle mode thrust can be accomplished if the failure occurs prior to about 29 minutes of MPS thrusting time (three-fourths of the way through the Mission Orbit Insertion burn) or if the failure occurs after about 39 minutes of MPS thrusting time (half-way through the Phasing Orbit Insertion burn).

Figures 4-11 and 4-12 together determine the alternatives available to a Tug which has undergone a failure to the idle mode thrust. For the previous case of an assumed failure to the idle mode after 25 minutes of cumulative nominal MPS thrusting, Figures 4-11 and 4-12 show that the deploy-only, intact abort, and jettison abort missions are possible alternatives while the complete replacement mission cannot be performed.

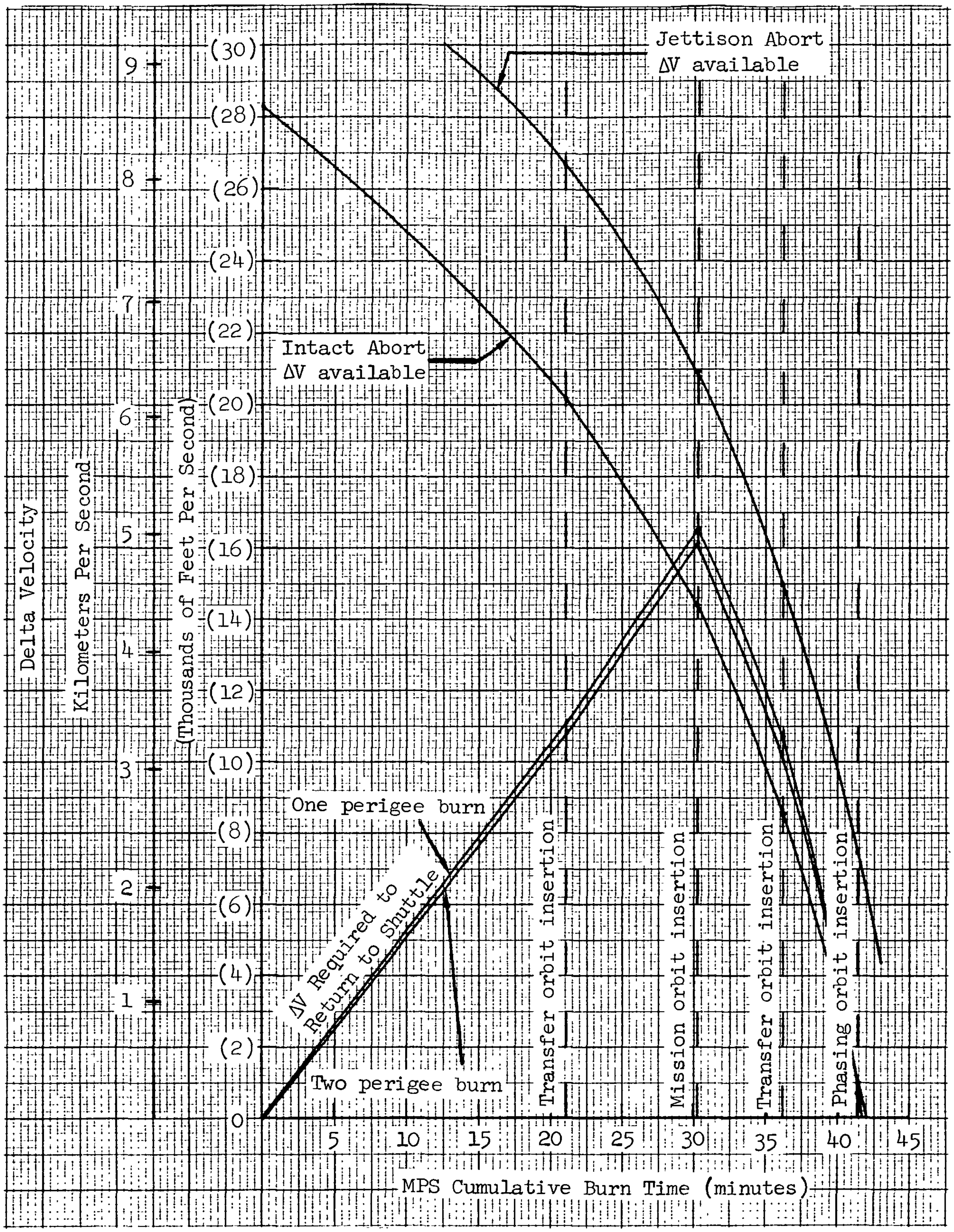


Figure 4-12. Intact Abort and Jettison Abort Capability Using Idle Mode Thrust

For an assumed failure in which only RCS thrust is available, Figure 4-13 shows the ability of the Tug to perform a complete replacement or a deploy-only mission. The available ΔV curve is based upon a multiple apogee and perigee burn scheme. The trajectory for an RCS thrust return from the descent transfer orbit, involving 10 apogee burns and 11 perigee burns, has been discussed earlier and is shown in Figure 4-10 and Table 4-14. The return from the mission orbit under RCS thrust would likewise require a total of 25 apogee and perigee burns.

Figure 4-13 indicates that a deploy-only mission using RCS thrust can be completed only if the failure occurs while the Tug is in the Mission Orbit. A complete replacement mission is possible only if the failure occurs after Phasing Orbit Insertion near the end of the mission.

The abort capability of the Space Tug under RCS thrust conditions is shown in Figure 4-14. The ΔV available for either an intact abort or a jettison abort under the reduced I_{sp} conditions of the RCS thrusters is plotted as a function of MPS cumulative burn time. Also plotted is the ΔV required to return to the Orbiter either on a continuous thrust trajectory such as that presented in Table 4-13 or on a multiple apogee and perigee burn trajectory such as the one pictured in Figure 4-10. The multiple burn curve of Figure 4-14 is based upon the 21-burn trajectory of Table 4-14 for a return from the descent transfer orbit and upon a 25-burn descent from the mission orbit. Clearly, the multiple burn trajectory offers significant ΔV savings as compared to the continuous thrust trajectory, especially for returns from the highly elliptical transfer orbits. (Continuous thrust is a relatively inefficient means of accomplishing a transfer between a highly elliptical and a circular orbit.)

In the case of a failure in which only the RCS thrust is available, Figure 4-14 shows that a jettison abort can always be accomplished. An intact abort can be accomplished if the failure occurs prior to 25.5 min of MPS accumulated thrust time (midway through the Mission Orbit Insertion burn)

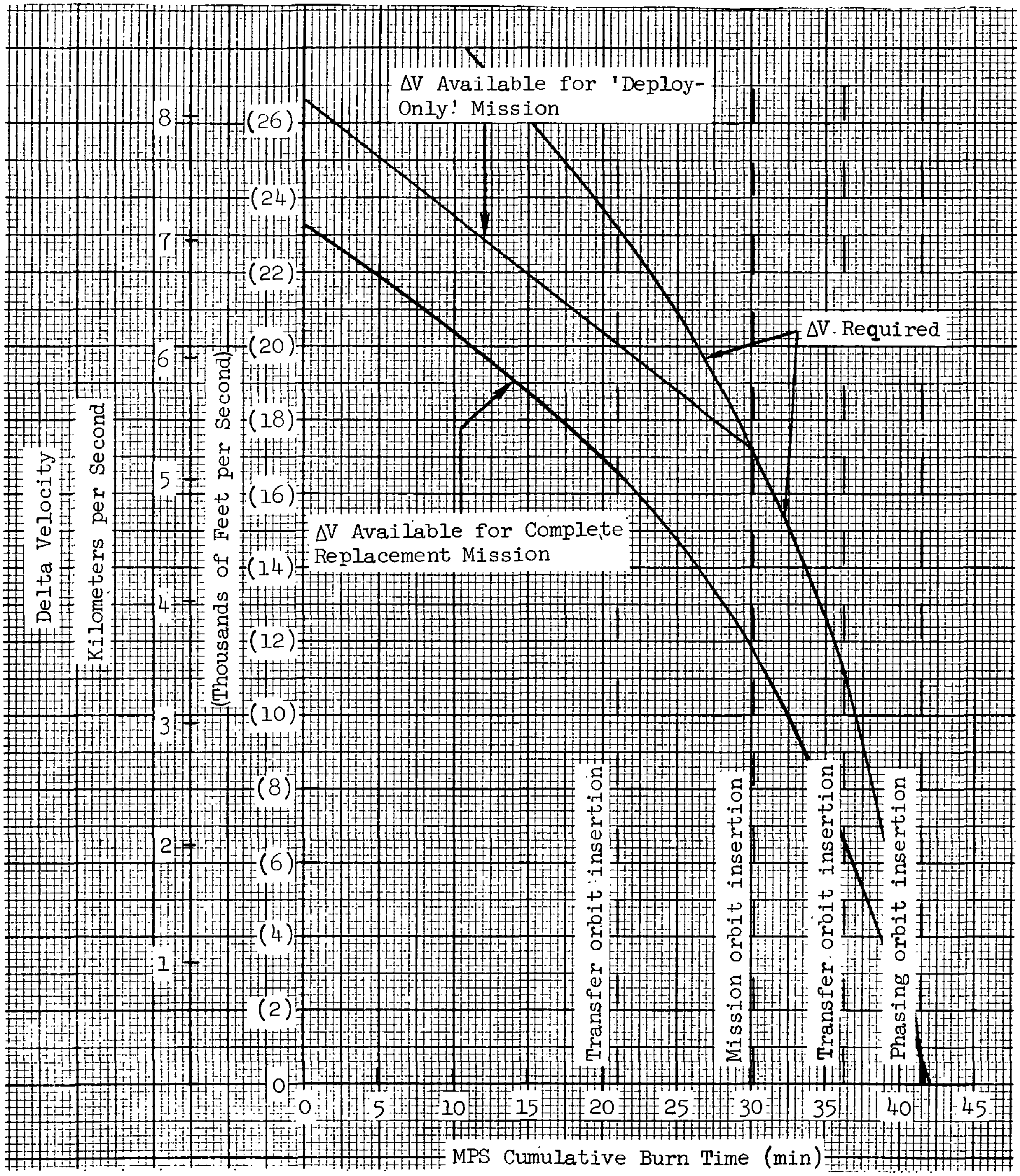


Figure 4-13. Capability to Perform Complete Replacement or Deploy-Only Mission Using RCS Thrust

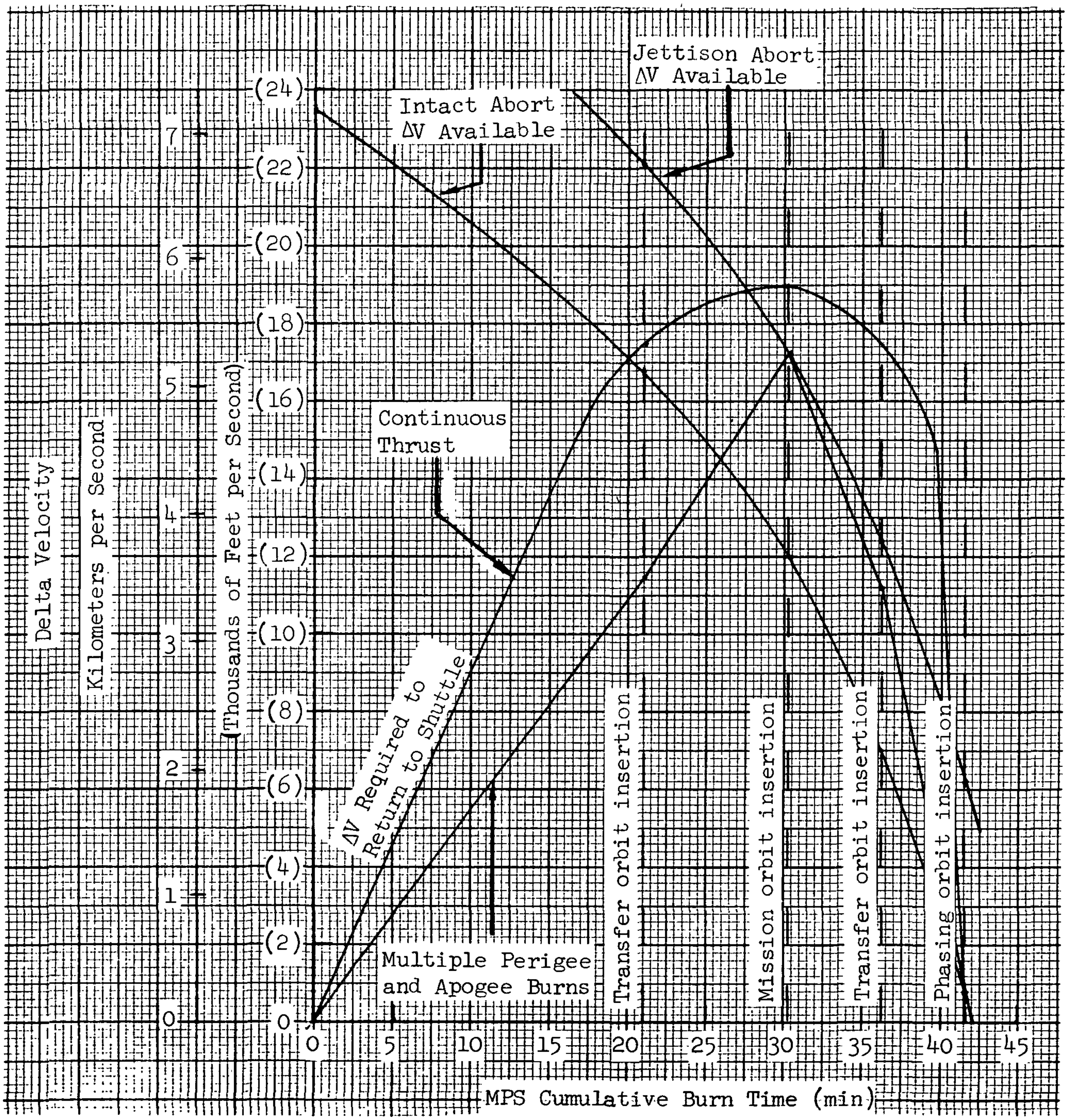


Figure 4-14. Tug Intact Abort and Jettison Abort Capability Using RCS Thrusters

or if the failure occurs after the Phasing Orbit Insertion burn (41.5 min of MPS burn time). Again, Figures 4-13 and 4-14 can be used together to determine the possible mission alternatives for a Space Tug using only RCS thrust at any point in the mission.

The capability of the Tug in a degraded thrust condition is summarized in Table 4-15. If an abort mission cannot be completed, the orbit in which fuel is exhausted in attempting to return to the Orbiter is given. For example, if a failure to the idle mode thrust occurs immediately prior to burn 4, the descent Transfer Orbit Insertion burn, then Table 4-15 indicates that an intact abort cannot be completed. The Tug and payload combination can, however, be propelled to a 315 × 2036 km (170 × 1100 nmi), 28.5 deg inclined orbit before the fuel is exhausted. Dash lines in place of an entry indicate that an alternative is meaningless. A deploy-only mission cannot physically be performed after burn 4 when the Tug and payload have deorbited from the mission orbit. Similarly, an intact abort (implying an abort with the payload attached) is meaningless immediately prior to burn 3 since the first payload has already been deployed and the second payload has not yet been retrieved.

As indicated in Table 4-15, portions of the mission can be performed in the event of a main engine failure provided there is idle mode or RCS thrust available. After the mission orbit has been obtained, the performance capabilities of the two alternate thrust modes are the same except that the idle mode thrust can bring the Tug and its payload back to a lower earth orbit in the case of an intact abort. If a failure occurs in the main engine prior to obtaining the mission orbit, a deployment-only mission can be completed using the idle mode thrust but not with the RCS thrust.

4. MINIMUM RETURN TIME

The Tug was assumed to have embarked upon a geosynchronous equatorial payload replacement mission from an Orbiter parking orbit of 296 × 296 km (160 × 160 nmi) at 28.5 deg inclination. At some point during the ascent transfer it was assumed necessary to return the Tug in as short

Table 4-15. Space Tug Degraded Mission and Abort Performance Summary

	Mission to be Attempted	Failure to Reduced Thrust is Assumed to Occur Prior to					
		Burn 1 Transfer Orbit Insertion	Burn 2 Mission Orbit Insertion	Burn 3 Retrieve Payload	Burn 4 Transfer Orbit Insertion	Burn 5 Phasing Orbit Insertion	Burn 6 Circularize
Idle Mode Thrust	Replacement	No	No	No	No	No	Yes
	Deploy-Only	Yes[1]	Yes	Yes	Yes	--	--
	Intact Abort	Yes	Yes	--	No 315 × 2036 km (170 × 1100 n mi) 28.5 deg	No 315 × 1944 km (170 × 1050 n mi) 28.5 deg	Yes
	Jettison Abort	Yes	Yes	Yes	Yes	Yes	Yes
RCS Thrusters[2]	Replacement	No	No	No	No	No	Yes
	Deploy-Only	No	No	Yes	Yes	--	--
	Intact Abort	Yes	Yes	--	No 315 × 5183 km (170 × 2800 n mi) 27.5 deg	No 222 × 4445 km (120 × 2400 n mi) 27.7 deg	Yes
	Jettison Abort	Yes	Yes	Yes	Yes	Yes	Yes

Yes — Mission can be completed.

No — Mission cannot be completed.

[1]Assumes double perigee burns are performed on both ascent and descent transfers.

[2]Assumes that multiple apogee and perigee burns are performed such as the trajectory of Figure 4-10 and Table 4-14.

a time as possible to a low earth orbit from which it could be retrieved by the Orbiter. The ascent transfer orbit was taken as 596 × 35,862 km (322 × 19,364 nmi) and inclined at 26.5 deg. The increase in perigee altitude from 296 km (160 nmi) was due to the finite burn effect of the Transfer Orbit Insertion maneuver using a 44,842 N (10,000 lb) thrust engine. The desired final orbit was a 315 × 315 km (170 × 170 nmi), 28.5 deg inclined orbit, coelliptic to that of the Orbiter. These orbiters are depicted in Figure 4-15.

Strictly speaking, there is no absolute minimum time return trajectory between an abort point on the ascent transfer orbit and the coelliptic orbit. The higher the ΔV available to perform the return, the lower the return time. However, for a given ΔV capability there is a trajectory from an abort point on the ascent transfer orbit to the coelliptic orbit which minimizes the return time. It is this minimum return time trajectory subject to the constraint of available ΔV which is sought in this analysis.

Table 4-16 shows the approximate impulsive ΔV capability of the Tug after the transfer orbit insertion maneuver. This ΔV of 5944 mps (19,500 fps) does not include contingency or reserve fuel but allows for gravity losses during the burns.

The method of analysis involved running a computer program which determines the velocity impulse required to perform the return given the departure or abort point, the arrival point, and the return time. This program was run for various abort points, arrival points, and return times. The minimum return time possible using the impulsive ΔV capability of the Tug for each abort point was then solved graphically. The results are shown in Figure 4-16 as a plot of minimum return time versus altitude of the abort period.

A typical minimum return time trajectory is shown in Figure 4-15. The Tug traverses the portion of the return ellipse shown in solid line. Using the ΔV capability of the Tug these return trajectories are always elliptical (insufficient ΔV capability exists to produce parabolic or

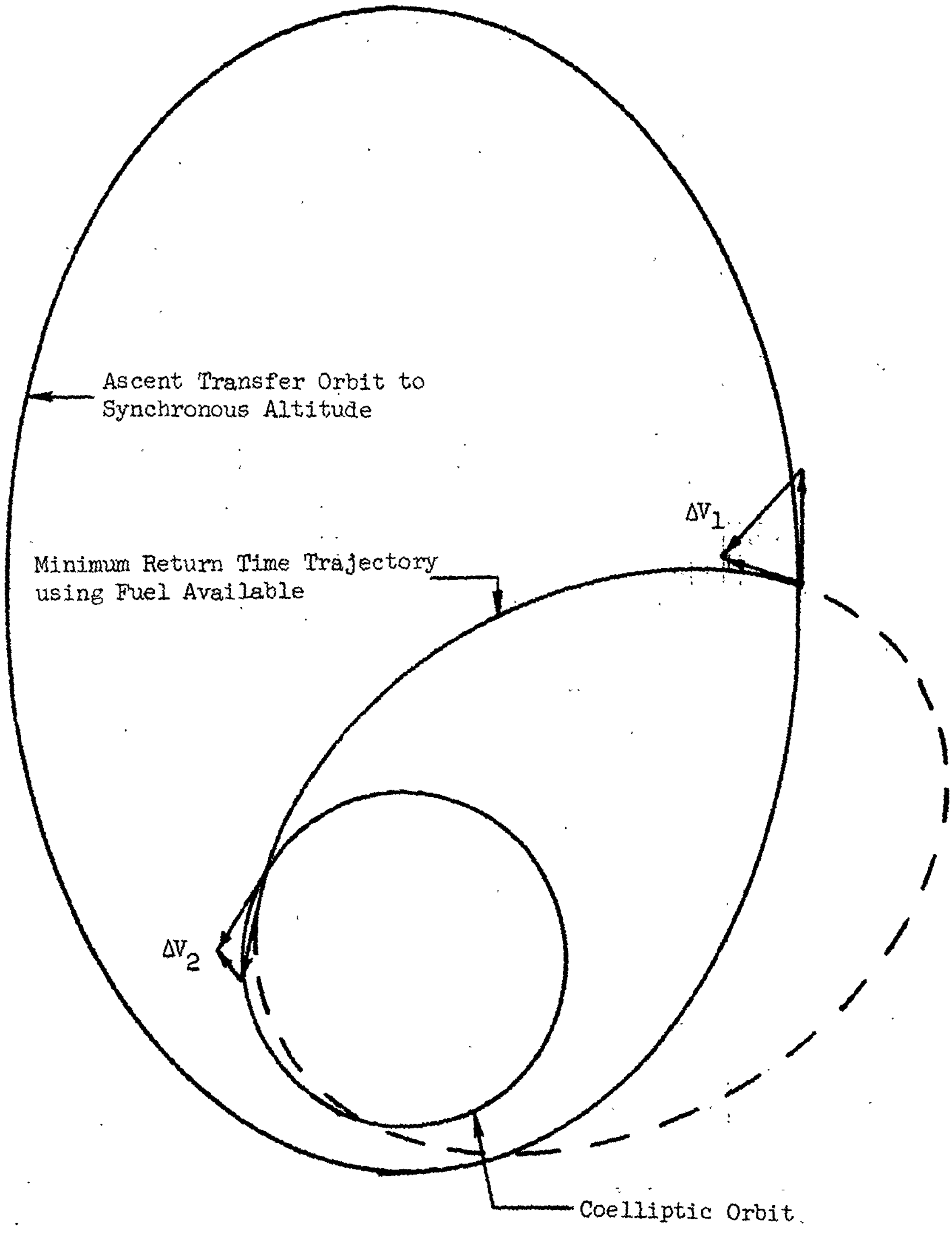


Figure 4-15. Space Tug Abort Configuration from Ascent Transfer Orbit

Table 4-16. Fuel Available After Transfer Orbit Insertion Burn

Total ΔV capability without contingency[1]	8660 mps	(28,411 fps)
Nominal TOI burn[1]	2542 mps	(-8340 fps)
ΔV capability after TOI burn	6118 mps	(20,071 fps)
Estimate of gravity losses	174 mps	(571 fps)
Approximate impulsive ΔV capability after TOI burn	5944 mps	(19,500 fps)

[1]From Ref. 5

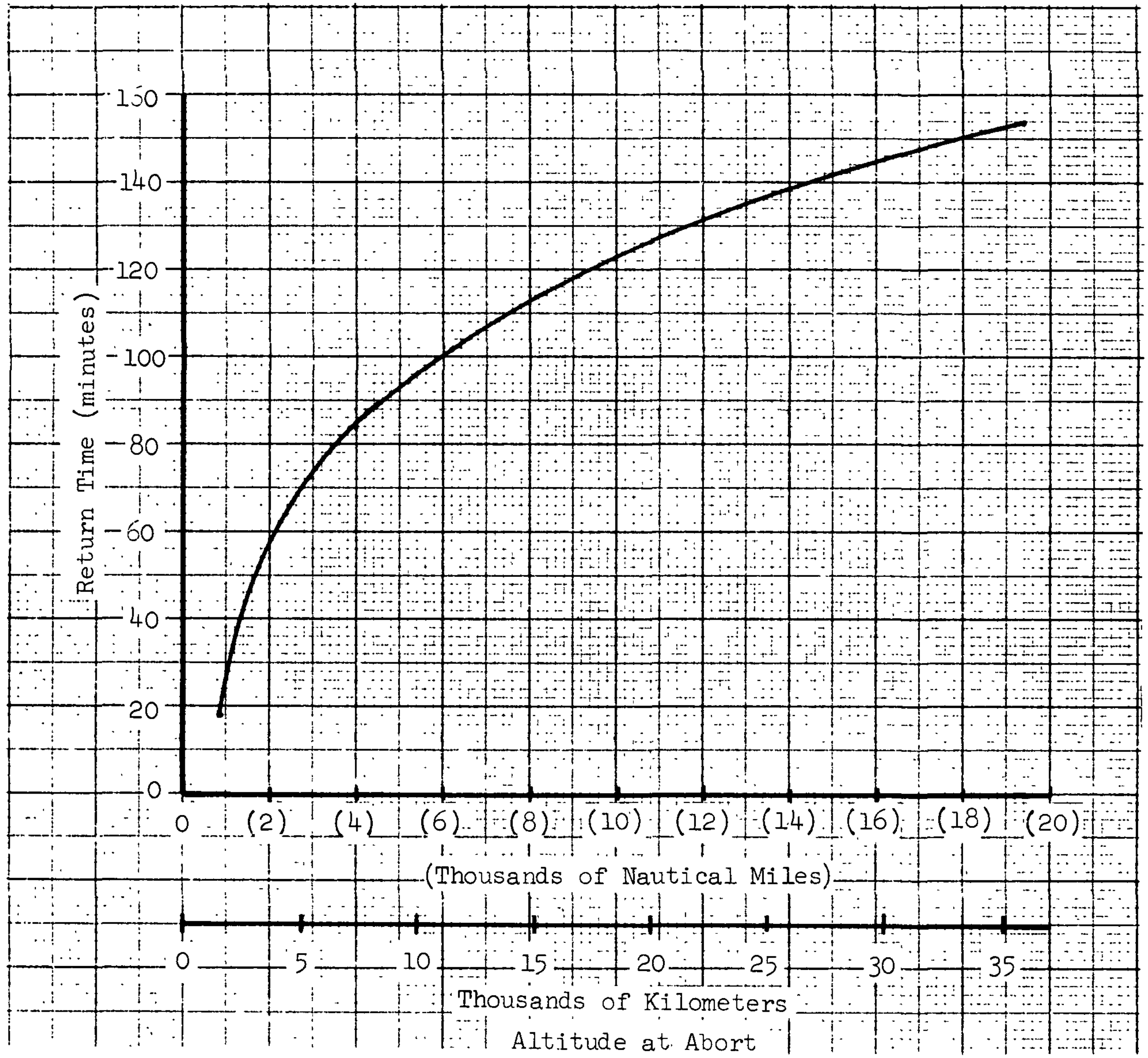


Figure 4-16. Minimum Return Times for Abort from Ascent Transfer Orbit

hyperbolic trajectories). Apogee altitude of the return trajectory is generally much higher than the altitude at abort, while the perigee altitude of the return trajectory generally falls between 269 and 315 km (145 and 170 nmi). The transfer, including plane change, is performed in two impulses shown as ΔV_1 and ΔV_2 in Figure 4-15.

F. TUG AUTONOMOUS ABORT ASSESSMENT

The ground support necessary for the STS elements during an abort situation is dependent on the on-board capabilities of the flight elements. A cursory assessment was made of the feasibility of incorporating an autonomous abort capability into the unmanned Tug vehicle. Functional requirements for Tug autonomous abort capability were defined and their impact on the design of the Tug on-board data management system was assessed. Rough estimates of software and hardware requirements were made, together with a projection of flight computer capability in the 1976-1980 time frame.

1. GENERAL CONSIDERATION FOR AUTONOMOUS CONTROL

The baseline mission of the Tug consists of a complex but well-ordered sequence of preplanned events controlled by the on-board data management subsystem. Conceptually, the timeline of events is similar to that of many existing unmanned flight programs. In particular, the functions of navigation, guidance, flight control, on-board subsystem interfacing, and external communications are well within the performance envelope of current state-of-the-art aerospace computers. The data storage requirements and computing power needed to control the Tug through its baseline mission can be estimated with some degree of confidence by a straightforward extension of some current flight programs.

The problem of dealing with non-nominal conditions is less well defined. The number of ways in which a complex system can exhibit

non-nominal performance is distressingly large, and the decision processes required to evaluate their impact on mission performance are correspondingly complex. Nevertheless, since non-nominal conditions have been known to occur in even the most carefully managed flight programs, some investigation into the feasibility of at least a limited degree of on-board diagnostic and mission reconfiguration capability appears worthwhile.

The sequence of actions involved with any non-nominal mission performance includes:

a. Detection of non-nominal condition
b. Isolation of problem
c. Assessment of resources available for coping with the problem
d. Selection of corrective action
e. Execution of corrective action.

Detection of non-nominal conditions is accomplished by adequate monitoring of all on-board subsystems. Figure 4-17 is a block diagram of the major on-board subsystems and their interfaces with the data management subsystem (DMS). Basically, the DMS accepts status information from subsystem instrumentation and transmits control signals to these subsystems. In addition, certain subsystems, such as the Inertial Measurement Unit (IMU), external sensors, docking subsystem, and the communications subsystem, are sources of digital input data to the computer. Typical flight programs perform on-board processing of external sensor data streams, but most current vehicles transmit raw status information obtained from subsystem instrumentation to the ground for data reduction and human evaluation.

On-board capability for detection of non-nominal conditions implies automation of at least the essential minimums of the human fault detection process. These are fairly straightforward. On-off switches, latches, valves, etc. are readily compared with their intended states. Variable parameters are easily tested against one or more tolerances. Of greater

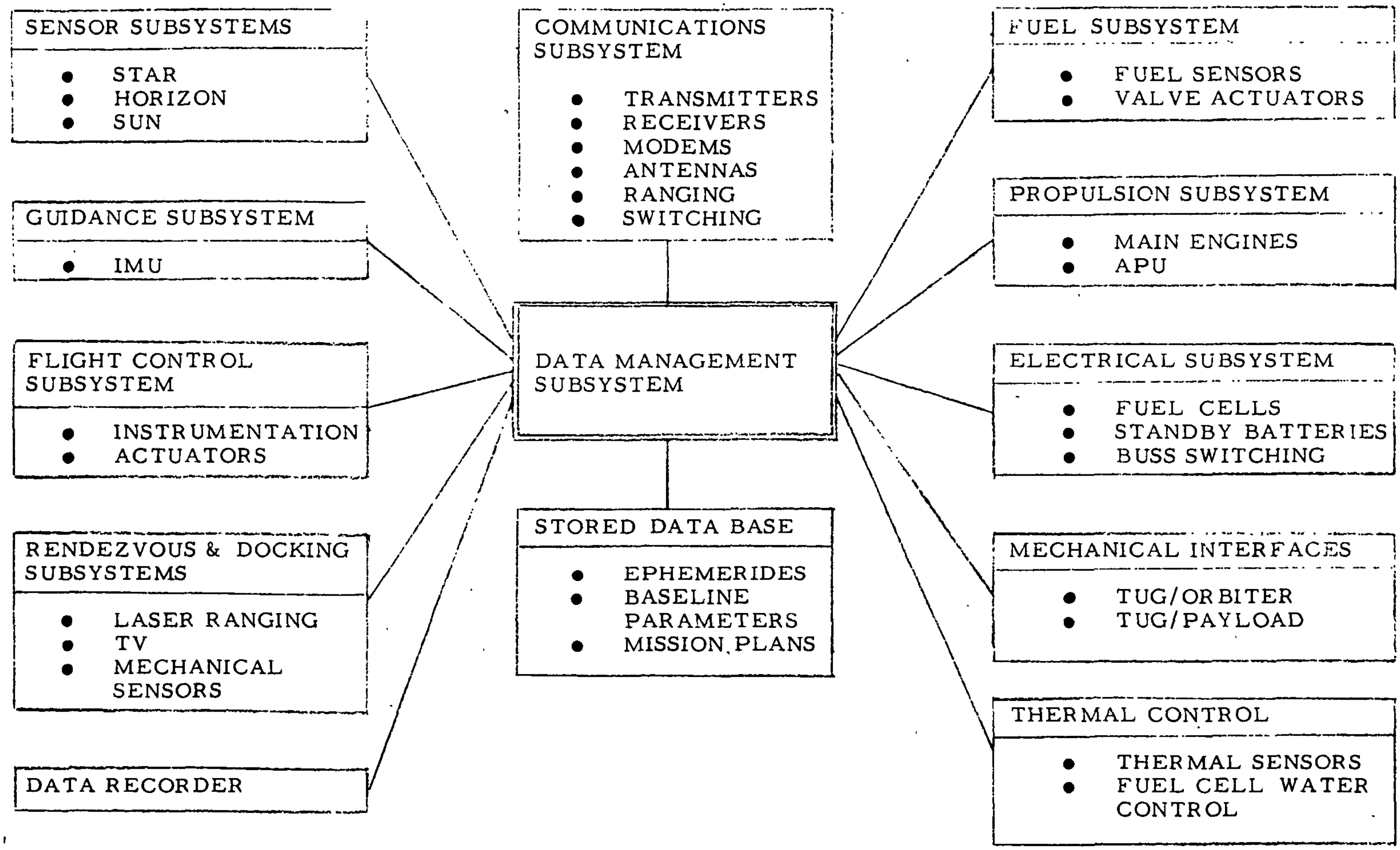


Figure 4-17. Data Management Subsystem Interfaces

significance, perhaps, is the detection of trends, for example a rising temperature indication that may be within allowable limits but which may provide a warning of some future problem. "Eyeball integration" of a strip chart recording may be difficult to emulate exactly in an on-board computer, but smoothed slope discrimination algorithms are available and should be incorporated where a parameter trend is a significant health indicator.

Isolation of a non-nominal condition follows detection in the sequence of actions involved with autonomous on-board control of the mission. In its simplest form, evaluation could consist simply of checking whether or not the detected anomaly is in a table of critical failures whose occurrence is fatal to completion of the mission as planned. The weakness of any single point evaluation concept is that a given non-nominal condition may arise from a multiplicity of underlying causes, and evaluation of the condition observed may not lead to a uniquely determinable conclusion as to the correct remedial actions. The diagnostic capability of a group of engineers intimately familiar with the vehicle, its subsystems, their interfaces, and how they interact is virtually impossible to achieve with a computer program of manageable size. Even the minimum capability is of some value, however, and represents a feasible starting point with considerable capacity for growth.

Assessment of on-board resource status is simply the updating of the baseline data from which a revised mission plan may be generated. The data required for status assessment is basically the same as those utilized in the fault detection process, together with the updated quantities of consumables, such as fuel and electric power.

Selection of a corrective action in response to a non-nominal condition consists of two sequential parts, the generation of a tentative plan, or sequence of events, required to accomplish the revised mission objective, and the verification of the plan, prior to putting it into effect, by a simulation of the sequence of events in the plan. The plan includes not only propulsion system burn times and durations, but also the schedules for attitude update events, thermal "toasting" maneuvers, latching and unlatching of various

mechanical subsystems, and so on. The subsequent verification process checks that not only does the generated plan meet the mission objectives, but also that all system constraints are observed, e.g., the horizon sensor may not be usable near local sunrise or sunset. If the verification process shows that certain constraints would be violated, mission parameters are adjusted, and a new plan is generated and reverified. The mission plan development process just described is ordinarily an interactive process involving humans for initial inputs and for parameter adjustment, and may require from hours to as long as several weeks to accomplish. The replacement of human judgment with suitable decision algorithms, and the compression of the time required for mission plan generation and verification are necessary steps in the achievement of an autonomous abort capability.

Execution of corrective action generated by the on-board mission planning process is straightforward, in that it involves the same concepts and techniques that are utilized in a conventional on-board data management system without autonomous abort capability.

2. ON-BOARD DATA MANAGEMENT SYSTEM REQUIREMENTS

This section discusses the software and hardware implications of adding autonomous abort capability to a baseline Tug data management system.

The software used for the various Titan III flight computers provides a useful benchmark, as it performs the functions of navigation, guidance, digital flight control, communications control, and limited system readiness monitoring. Typically these functions require 8K-12K words of storage, and an effective instruction execution rate of 50K to 100K instructions per second. The trend is toward more sophisticated programs, and more recent flight computers have been configured with 16K words of storage.

Studies of Tug on-board computational requirements (Ref. 25) derive a maximum program storage requirement of about 150K bytes, or 37, 500 32-bit words, allocated as shown in Table 4-17. A comparison with

Table 4-17. Storage Requirements for Tug On-Board Computer (from Ref. 25)

Function	Storage (Bytes)
Navigation	25K
Guidance	14K
Flight Control	3K
Mission Planning	25K
Mission Verification	20K
System Readiness	17K
Digital Communications	16K
Display	8K
Executive and Utility	22K
Total	150K bytes

(Equivalent to 37.5K 32-bit words)

existing ground programs performing subsets of the complex system readiness, mission planning, and mission verification functions may be made to provide an upper bound on the size and test the credibility of these estimates. Typical system readiness checkout programs for 700 to 1000 measurement points generally require in the neighborhood of 16K words of storage, but this provides only printed output of non-nominal values, not automated evaluation, this being left to the engineer monitoring the checkout. To add some automated trend analysis capability is estimated to require another 4K storage locations.

An instruction count estimate for an on-board mission planning capability is difficult to estimate. The number of events in the plan is, of course, a function of the duration and complexity of the mission. Presumably, however, since an abort situation cuts the nominal mission short, the abort plan is shorter than the original mission plan it replaces. Although there are no existing programs suitable for direct comparison, it seems probable that the estimate of 25K bytes for mission planning contained in Table 4-17 may be low by a factor of four or five, i.e., 25K-30K 4-byte words of storage is a more reasonable estimate. Similarly, a feel can be gained of the potential size of the mission verification program, by examining trajectory simulation programs such as MVS, or MPP. MVS (Modularized Vehicle Simulator) uses over 60K 60-bit words in a complex overlay structure, requires extensive manual input preparation, and may take minutes to model a trajectory on a CDC 7600. MPP (Mission Planning Program) is also a large program (on the order of 100K words), and also requires extensive manual input preparation. Even though neither of these programs was designed specifically for automatic mission verification, the simulation approach is applicable, and a rough sizing comparison is probably valid within a factor of two.

Simply combining the admittedly rough revised estimates with the other computer storage requirements set forth in Ref. 25 would result in a total on-board memory requirement approaching 132K words (Table 4-18)

Table 4-18. Storage Requirements for Tug On-Board Computer Including Autonomous Abort

Function		Storage (Bytes)
Navigation		25K
Guidance		14K
Flight Control		3K
Mission Planning		120K
Mission Verification		240K
System Readiness		80K
Digital Communications		16K
Display		8K
Executive and Utility		22K
	Total	528K bytes

(Equivalent to 132K 32-bit words)

compared with the 38K (150K bytes) suggested in Ref. 25. This number would probably be an upper bound on the storage requirement. The following additional factors should be considered in order to test the credibility of the lower estimate:

a. The ground software prepared for use on the commercial computers is typically written in FORTRAN. The compilers for commercial machines are usually quite inefficient in use of storage with a factor of two being a reasonable estimate.

b. The number of storage locations does not involve packing of instructions. The flight computers would most likely have the capability of packing two 16-bit instructions into a 32-bit storage word. This would allow a significant reduction in the number of storage locations.

c. The full mission planning capability of the ground program would probably not be required for the in-flight abort planning for the Tug. For example, atmospheric ascent phases would not have to be considered. Guidance steering algorithms would not have to be included in the mission planning but would have to be called only as required.

Consequently, though 38K may be optimistic and 132K pessimistic, a computer size of 64K words would appear to be appropriate.

3. HARDWARE CONSIDERATIONS

The technical factors governing the design of the Tug on-board data management system include computing speed, size, weight, power consumption, and reliability. These factors must be considered in terms of the technology postulated to be available in the 1976-1980 time frame.

Computing speed, in terms of memory access, add time, and multiply times, would appear to pose no severe problems. Access times for metal oxide semiconductor (MOS) memories range from 900 nanoseconds down to about 300 nanoseconds, and are already replacing magnetic cores for mainframe memory applications. A hybrid approach using bipolar circuitry for fast working memory and MOS for main memory will result in some improvement over the current performance limits of about one microsecond for addition and 5-10 microseconds for multiplication.

The physical characteristics of size, weight, and power consumption can be expected to show some improvement over currently produced aerospace computers; some typical characteristics of currently available computers are shown in Table 4-19. It should be noted that the largest working storage capacity actually being built for delivery is 16K words, although some models have the capability of directly addressing up to 128K words. Word length, which varies from 16 to 32 bits among current computer designs, is trending toward the larger word length, primarily because of the need to provide the higher number of address bits required to access the larger memory configurations.

The current trends in large scale integration (LSI) techniques should allow achieving a volume of two cubic feet or less, not including power conversion electronics. The weight of the computer will be dependent mainly on the weight of the memory components and associated power supplies, with an overall weight of 23 to 34 kg (50 to 75 lb) appearing to be a feasible goal.

Power consumption is strongly dependent on the access time to directly addressable memory, as MOS storage is an active refresh-type memory. To keep total power consumption under the DMS baseline of 275 W may require allocating a portion of the storage requirement to a slower auxiliary memory with consequently lower power consumption.

The reliability of MOS-LSI circuitry is very high. Predicted MTBF figures for some recent small LSI technology computers approach 15,000 hours. An essential characteristic of any system whose objective is to diagnose and compensate for faulty performance in another system is that it be much more reliable than the system being controlled. This condition will, in all probability, be satisfied easily. Reliability of DMS circuitry will continue to improve. Other mass data storage techniques, such as magnetic bubble memories, appear promising in terms of compactness and low power consumption; but, because they are in an early developmental stage, it is not possible to predict what their capabilities will be in the 1976-1980 time frame.

Table 4-19. Typical Flight Computer Characteristics

Make	Word Size	Memory Capacity	Memory Type	Memory Cycle/Access (μsec)	Size	Weight	Power
IBM 4 /EP	32 bits	16K-128K	Core	2.5/0.9	0.025 m^3 (0.9 ft^3)	28 kg (62 lb)	303 W
UNIVAC 1824	24 bits (data) 16 bits (inst.)	500 (DRO) 12K (NDRO)	Thin Film	4.0/0.7	0.014 m^3 (0.5 ft^3)	15 kg (32 lb)	110 W
DELCO Magic 352	24	16K-32K	Core	3.0/1.5	0.03 m^3 (1.05 ft^3)	31 kg (68 lb)	85 W (220 with I/O)
CDC 469	16 bits	4K-65K	Plated Wire	1.6/0.8	0.003 m^3 (0.1 ft^3)	1 kg (3 lb)	15 W (4K)
RCA Marc 1	16 bits	4K-65K 8K ROM	Semi-conductor	1.5/1.5	0.008 m^3 (0.3 ft^3)	4 kg (9 lb)	4.2 W (small-config.)

4. RECOMMENDATIONS

This preliminary analysis of data management system requirements for Tug autonomous abort capability has permitted a general definition of the scope of the problem and the development of some broad guidelines for further steps in the systems analysis/development process.

The greatest single uncertainty factor in determining the overall feasibility of incorporating an autonomous abort capability in the Tug data management system is the question as to whether the functions now performed by human beings in the areas of fault diagnosis, mission plan generation, and mission plan verification can be automated to any useful degree. This problem should receive high priority in any follow-on study plan.

The task of software development will be facilitated by identifying non-overlapping functional areas and defining "clean" interfaces among them. This modular approach not only permits program design efforts to proceed in parallel, but also creates a structure where one module can be modified with minimal impact on the rest of the system. The modular approach to software design permits maximum utilization of previously developed algorithms.

The question of a modular versus an integrated hardware configuration has been the subject of many studies. The increasing reliability of digital computer systems favors the use of an integrated system. The integrated system offers maximum flexibility in software implementation. It should be noted also that connectors have historically been among the most troublesome components from a reliability viewpoint. The finite probability of human error in plugging together units during assembly and test cannot be ignored.

In conclusion, it is recommended that functional analyses and software concept studies be conducted assuming computer availability in the 1976-1980 time frame approximately as follows:

Memory Capacity -	64 K 32-bit words (access time 0.3 μsec)
Computing Speeds -	Add Time < 1 μsec Mult Time < 5 μsec
Volume -	$<0.057\ m^3$ ($2\ ft^3$)
Weight -	<22.5 kg (50 lb)
Power Consumption -	~275 W

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APPENDIX A. COST ESTIMATING RELATIONSHIPS

The following Cost Estimating Relationships (CERs) relate to the Space Tug and have been extracted verbatim from paragraph 4.7 of Reference 3.

Launch Operations

$$\begin{bmatrix}\text{Launch}\\ \text{Operations}\\ \text{Cost}\end{bmatrix} = (5.5 \times 10^{4}) \left\{ \begin{bmatrix}\text{No. of}\\ \text{Launches}\\ \text{Per Year}\\ \text{Site \#1}\end{bmatrix}^{0.60} + \begin{bmatrix}\text{No. of}\\ \text{Launches}\\ \text{Per Year}\\ \text{Site \#2}\end{bmatrix}^{0.60} \right\} \begin{bmatrix}\text{No. of}\\ \text{Years}\\ \text{Operational}\\ \text{Program}\end{bmatrix}$$

Recovery Operations

$$\begin{bmatrix}\text{Recovery}\\ \text{Operations}\\ \text{Cost}\end{bmatrix} = (8.5 \times 10^{3}) \left\{ \begin{bmatrix}\text{No. of}\\ \text{Launches}\\ \text{Per Year}\\ \text{Site \#1}\end{bmatrix}^{0.60} + \begin{bmatrix}\text{No. of}\\ \text{Launches}\\ \text{Per Year}\\ \text{Site \#2}\end{bmatrix}^{0.60} \right\} \begin{bmatrix}\text{No. of}\\ \text{Years}\\ \text{Operational}\\ \text{Program}\end{bmatrix}$$

Replacement Training

$$\begin{matrix}\text{Ground Crew}\\ \text{Replacement}\\ \text{Training}\end{matrix} = (0.25) \begin{bmatrix}\text{Total}\\ \text{No. of Ground}\\ \text{Crew Members}\end{bmatrix} (17{,}250)$$

Command and Control

$$\begin{bmatrix}\text{Command}\\\text{and}\\\text{Control}\\\text{Cost}\end{bmatrix} = (35,400)\left\{\begin{bmatrix}\text{Annual}\\\text{No. of}\\\text{Man Years}\\\text{Site \#1}\end{bmatrix} + \begin{bmatrix}\text{Annual}\\\text{No. of}\\\text{Man Years}\\\text{Site \#2}\end{bmatrix}\right\} \begin{bmatrix}\text{No. of}\\\text{Years}\\\text{Operational}\\\text{Program}\end{bmatrix}$$

Facility and Equipment Maintenance

$$\begin{bmatrix}\text{Facility}\\\text{Maintenance}\\\text{Cost}\end{bmatrix} = (0.05)\left\{\begin{bmatrix}\text{Launch}\\\text{Facility}\\\text{Cost}\\\text{(RDT\&E)}\end{bmatrix} + \begin{bmatrix}\text{Operations}\\\text{Facility}\\\text{Cost}\\\text{(RDT\&E)}\end{bmatrix} + \begin{bmatrix}\text{Launch}\\\text{Facility}\\\text{Cost}\\\text{(Investment)}\end{bmatrix} + \begin{bmatrix}\text{Operations}\\\text{Facility Cost}\\\text{(Investment)}\end{bmatrix}\right\} \begin{bmatrix}\text{No. of Years}\\\text{Operational}\\\text{Program}\end{bmatrix}$$

$$\begin{bmatrix}\text{Equipment}\\\text{Maintenance}\\\text{Cost}\end{bmatrix} = 0.05\left\{\begin{bmatrix}\text{Ground and}\\\text{Support}\\\text{Equipment}\\\text{(RDT\&E)}\end{bmatrix} + \begin{bmatrix}\text{Propellant}\\\text{Production}\\\text{Equipment}\\\text{(RDT\&E)}\end{bmatrix} + \begin{bmatrix}\text{Ground and}\\\text{Support}\\\text{Equipment}\\\text{(Investment)}\end{bmatrix} + \begin{bmatrix}\text{Propellant}\\\text{Production}\\\text{Equipment}\\\text{(Investment)}\end{bmatrix}\right\} \begin{bmatrix}\text{No. of Years}\\\text{Operational}\\\text{Program}\end{bmatrix}$$

Vehicle Maintenance

$$\begin{bmatrix}\text{Ground-Based}\\ \text{Maintenance}\\ \text{Operations}\\ \text{Cost}\end{bmatrix} = \left\{ 1.82 \times 10^5 \left[\begin{pmatrix}\text{No. of Launches}\\ \text{Per Year}\\ \text{Site \#1}\end{pmatrix}^{0.60} + \begin{pmatrix}\text{No. of Launches}\\ \text{Per Year}\\ \text{Site \#2}\end{pmatrix}^{0.60} \right] + \left[\frac{(3.4 \times 10^5)\ (\text{Total Number of Launches})}{(\text{Number of flights between overhaul})} \right] \right\} \begin{bmatrix}\text{No. of}\\ \text{Years}\\ \text{Operational}\\ \text{Program}\end{bmatrix}$$

In-Plant Engineering Support

$$\begin{bmatrix}\text{In-Plant}\\ \text{Engineering}\\ \text{Support Cost}\end{bmatrix} = \begin{bmatrix}\text{No. of Annual}\\ \text{Direct}\\ \text{Engineering}\\ \text{Man Years}\end{bmatrix} \left[(42,000) \right] \begin{bmatrix}\text{No. of Years}\\ \text{Operational}\\ \text{Program}\end{bmatrix}$$

Payload Integration and Management

$$\begin{bmatrix} \text{Program} \\ \text{Integration and} \\ \text{Management} \\ \text{Cost} \end{bmatrix} = (42,000) \left\{ \begin{bmatrix} \text{No. of} \\ \text{Annual} \\ \text{Direct} \\ \text{Manyears} \\ \text{of Effort} \\ \text{Site \#1} \end{bmatrix} + \begin{bmatrix} \text{No. of} \\ \text{Annual} \\ \text{Direct} \\ \text{Manyears} \\ \text{of Effort} \\ \text{Site \#2} \end{bmatrix} \right\} \begin{bmatrix} \text{No. of} \\ \text{Years} \\ \text{Operational} \\ \text{Program} \end{bmatrix}$$

Spares Support

$$\begin{bmatrix} \text{Total} \\ \text{Spares} \\ \text{Cost} \end{bmatrix} = \begin{bmatrix} \text{Initial} \\ \text{Spares} \\ \text{Cost} \end{bmatrix} \begin{bmatrix} \text{Number of} \\ \text{Launches} \\ \text{Per year} \end{bmatrix} \begin{bmatrix} \text{Spares} \\ \text{Use} \\ \text{Factor} \end{bmatrix} \begin{bmatrix} \text{Number of} \\ \text{Years of} \\ \text{Operations} \end{bmatrix}$$

Systems Element / Spares Element	TUG			
	Overhaul Period (N LOH)	Sched. Repl. Factor (SRF)	Unsched. Repl. Factor (URF)	Spares Use Factor
Structure (1)	10	0.05	0.002	0.007
Thermal Protection System	← Not Appl →			
Rocket Engines	10	0.20	0.0015	0.0215
Airbreathing Engines	← Not Appl →			
Subsystems (2)	10	0.25	0.005	0.030

Notes: (1) Includes Aerodynamic Surfaces and Body/Tank Structure.
(2) Includes Avionics, Power Supply & Distribution, ECLS, Emergency Recovery, Orientation Control.

Propellant Support

$$\begin{bmatrix}\text{Basic}\\\text{Propellant}\\\text{Cost}\end{bmatrix} = \begin{bmatrix}\text{Weight}\\\text{of}\\\text{Propellant}\end{bmatrix}\begin{bmatrix}\text{Cost per}\\\text{Pound of}\\\text{Propellant}\end{bmatrix}\begin{bmatrix}\text{Total No.}\\\text{of Flights}\\\text{per Year}\\\text{Sites 1 and 2}\end{bmatrix}\begin{bmatrix}\text{No. of}\\\text{Years of}\\\text{Operational}\\\text{Program}\end{bmatrix}$$

The costs of propellants are

O_2/H_2 $0.13/lb

H_2 $0.60/lb

Range/Base Support

$$\begin{bmatrix}\text{Range/Base}\\\text{Support}\\\text{Costs}\end{bmatrix} = 35,400\left[\begin{pmatrix}\text{No. of}\\\text{Annual}\\\text{Direct}\\\text{Man Years}\\\text{Site \#1}\end{pmatrix} + \begin{pmatrix}\text{No. of}\\\text{Annual}\\\text{Direct}\\\text{Man Years}\\\text{Site \#2}\end{pmatrix}\right]\begin{bmatrix}\text{No. of}\\\text{Years}\\\text{Operational}\\\text{Program}\end{bmatrix}$$

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APPENDIX B. GROSS ABORT EFFECTS ON STS ELEMENTS

For each of the abort regimes defined for the baseline mission (refer to Section 4. D. 1 in the main body of this report), the gross effects on each of the STS elements, viz., the Orbiter, Tug, payload, and ground facilities of an abort-producing failure in one of the STS flight elements were assessed. This assessment was not concerned with the actual failure mode of the element, but merely assumed that a failure had occurred in the element which resulted in an abort. For this abort assessment, it was assumed that no aborts (immediate return to landing site) would be dictated by a Tug or payload failure during powered Shuttle ascent flight. All Tug or payload failures were assumed to be fail-safe in nature relative to the Orbiter. In the event of a Tug or payload failure, the Orbiter would continue on to a stable orbit at which time an abort procedure could be initiated dependent on the type of failure.

The results of the gross abort effects assessment are tabulated in Table B-1. Listed in the table are the abort regime, the flight element in which the failure occurred, the action taken as a result of the failure, and the effects on the STS elements. In many of the abort regimes, several of the flight elements were assumed to have sustained more than one type of failure which resulted in different abort actions. For example, in abort regime XI, the Tug was assumed to have experienced three different types of failures (see cases 36, 37, and 38). In case 36, the Tug was assumed to have incurred a failure which prohibited the Tug from continuing the mission but did not prevent the Tug from phasing and returning to the Orbiter. In case 37, the Tug was not able to properly phase with the Orbiter and in case 38 the payload was dumped in an off-nominal orbit. These three different types of failures resulted in different effects on the remaining STS elements

as is shown in Table B-1. Hence, without actually defining the particular failure, different gross effects were determined for different types of failures.

In the 63 cases listed in Table B-1, there are only a few different gross effects on each of the elements. This is a result of the similarity of the abort actions taken in many of the abort regimes. The different gross effects are summarized and discussed in Section 4.D.2 in the main body of this report.

Table B-1. Gross Abort Effects on STS Elements

CASE	ABORT REGIME	ELEMENT FAILED	ABORT ACTION	EFFECT ON ELEMENTS
1	I	Tug	None. Continue ascent to stable orbit.	ORBITER - Assess Tug failure. Provide for Tug propellant dump for return to earth if necessary. TUG - Perform self-check and provide data to Orbiter for abort assessment. Dump propellant for return to earth if necessary. PAYLOAD - Returned to earth prematurely. GROUND - Flight elements returned to ground prematurely.
2	I	Payload	None. Continue ascent to stable orbit.	ORBITER - Provide for Tug propellant dump for return to earth if necessary. TUG - Dump propellant for return to earth if necessary. PAYLOAD - Same as Case 1. GROUND - Same as Case 1.
3	I	Shuttle	Continue ascent to reach sufficient altitude and velocity for glideback to launch site.	ORBITER - Provide for Tug propellant dump or land with full Tug. TUG - Dump propellants or land with full or partially full tanks. PAYLOAD - Withstand abort landing loads. GROUND - Flight elements returned to ground prematurely. May have to handle full or partially fueled Tug.
4	II	Tug	None. Continue ascent to stable orbit.	Same as Case 1.
5	II	Payload	None. Continue ascent to stable orbit.	Same as Case 2.
6	II	Shuttle	Shut down Orbiter engines and glide back to launch site.	Same as Case 3.

Table B-1. Gross Abort Effects on STS Elements (continued)

CASE	ABORT REGIME	ELEMENT FAILED	ABORT ACTION	EFFECT ON ELEMENTS
7	IIIa	Tug	None. Continue ascent to stable orbit.	Same as Case 1.
8	IIIa	Payload	None. Continue ascent to stable orbit.	Same as Case 2.
9	IIIa	Shuttle	Powered return to launch site.	Same as Case 3.
10	IIIb	Tug	None. Continue ascent to stable orbit.	Same as Case 1.
11	IIIb	Payload	None. Continue ascent to stable orbit.	Same as Case 2.
12	IIIb	Shuttle	Powered return to launch site.	Same as Case 3.
13	IV	Tug	None. Continue ascent to stable orbit.	Same as Case 1.
14	IV	Payload	None. Continue ascent to stable orbit.	Same as Case 2.
15	IV	Orbiter	Orbiter aborts to once-around orbit.	Same as Case 3.
16	V	Tug	None. Continue ascent to stable orbit.	Same as Case 1.
17	V	Payload	None. Continue ascent to stable orbit.	Same as Case 2.
18	V	Orbiter	De-orbit and return to launch site (cannot deploy).	Same as Case 3.
19	V	Orbiter	Deploy Tug/payload and return to launch site.	ORBITER - Deploy Tug/payload in 93 × 185 km (50 × 100 nmi) orbit. TUG - Provide ΔV for circularization at 185 km (100 nmi) orbit. PAYLOAD - Subjected to different "q" loading at 93 km (50 nmi). GROUND - Orbiter returned to ground prematurely.
20	VI	Same as for abort regime V.		

Table B-1. Gross Abort Effects on STS Elements (continued)

CASE	ABORT REGIME	ELEMENT FAILED	ABORT ACTION	EFFECT ON ELEMENTS
21	VII	Tug	Shuttle return to launch site with Tug/payload.	Same as Case 1.
22	VII	Payload	Shuttle return to launch site with Tug/payload.	Same as Case 2.
23	VII	Orbiter	De-orbit and return to launch site (cannot deploy).	Same as Case 3.
24	VII	Orbiter	Deploy Tug/payload and return to launch site.	ORBITER - Return to earth prematurely. TUG - Provide ΔV to perform mission from orbit lower than 296 km (160 nmi) circular. PAYLOAD - None. GROUND - Orbiter returned prematurely.
25	VIII	Tug	Orbiter return to launch site with Tug/payload.	Same as Case 1.
26	VIII	Payload	Orbiter return to launch site with Tug/payload.	Same as Case 2.
27	VIII	Orbiter	De-orbit and return to launch site (cannot deploy).	Same as Case 3.
28	VIII	Orbiter	Deploy Tug/payload and return to launch site.	Same as Case 24.
29	IX	Tug	Orbiter return to launch site with Tug/payload.	Same as Case 1.
30	IX	Payload	Orbiter return to launch site with Tug/payload.	Same as Case 2.
31	IX	Orbiter	De-orbit and return to launch site (cannot deploy).	Same as Case 3.
32	IX	Orbiter	Deploy Tug/payload and return to launch site.	ORBITER - Return to earth prematurely. TUG - None. Complete mission. Return to parking orbit and wait for retrieval.

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Table B-1. Gross Abort Effects on STS Elements (continued)

CASE	ABORT REGIME	ELEMENT FAILED	ABORT ACTION	EFFECT ON ELEMENTS
				PAYLOAD - None. Complete mission. GROUND - Orbiter returned to earth prematurely.
33	X	Tug	Orbiter retrieve Tug/payload and return to launch site.	ORBITER - Must retrieve a disabled Tug. Returned to earth prematurely. TUG - Dump propellants and safe itself prior to redocking with Shuttle. PAYLOAD - Returned to earth prematurely. GROUND - Flight elements returned to earth prematurely.
34	X	Payload	Orbiter retrieve Tug/payload and return to launch site.	ORBITER - Retrieve a Tug with a disabled payload. Returned to earth prematurely. TUG - Dump propellants and safe itself prior to redocking with Orbiter. Interface with a disabled payload. PAYLOAD - Returned to earth prematurely. GROUND - Flight elements returned to earth prematurely.
35	X	Orbiter	Orbiter return to earth.	Same as Case 32.
36	XI	Tug	Tug phase and return to parking orbit.	ORBITER - Dock with Tug/ payload and return to earth prematurely. TUG - Determine proper phasing to return to parking orbit for rendezvous and docking with Orbiter. PAYLOAD - Returned to earth prematurely. GROUND - Flight elements returned to earth prematurely.

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Table B-1. Gross Abort Effects on STS Elements (continued)

CASE	ABORT REGIME	ELEMENT FAILED	ABORT ACTION	EFFECT ON ELEMENTS
37	XI	Tug	Tug return to parking orbit not phased with Orbiter.	ORBITER - Perform phasing orbiter maneuver for rendezvous with Tug or return to earth without Tug (effect dependent on time required for return of Tug to parking orbit). TUG - Return to parking orbit. Wait for retrieval. PAYLOAD - Not deployed and waits in parking orbit for retrieval by Orbiter. GROUND - Possible early or late return of flight elements.
38	XI	Tug	Tug dump payload and return to parking orbit not phased with Orbiter.	ORBITER - Perform phasing orbit maneuver for rendezvous with Tug or return to earth without Tug (effect dependent on time required for return of Tug to parking orbit). TUG - Return to parking orbit and wait for retrieval. PAYLOAD - Placed in off-nominal orbit. Possible retrieval by another flight. GROUND - Possible early return of some flight elements.
39	XI	Payload	Tug phase and return to parking orbit.	Same as Case 36.
40	XI	Orbiter	Orbiter return to earth.	ORBITER - Return to earth prematurely. TUG - Continue mission. May be picked up by another Orbiter flight. PAYLOAD - Continue mission. GROUND - Early return of Orbiter.

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Table B-1. Gross Abort Effects on STS Elements (continued)

CASE	ABORT REGIME	ELEMENT FAILED	ABORT ACTION	EFFECT ON ELEMENTS
41	XII	Tug	Tug phase and return to parking orbit.	ORBITER - Dock with Tug and return to earth prematurely. TUG - Determine proper phasing to return to parking orbit for rendezvous and docking with Orbiter. PAYLOAD - Returned to earth prematurely. GROUND - Early return of flight elements.
42	XII	Tug	Tug dump payload, phase, and return to parking orbit.	ORBITER - Dock with Tug and return to earth prematurely. TUG - Determine proper phasing to return to parking orbit for rendezvous and docking with Orbiter. PAYLOAD - Placed in sync orbit but not in correct position. GROUND - Early return of flight elements.
43	XII	Tug	Tug return to parking orbit not phased with Orbiter.	Same as Case 37.
44	XII	Tug	Tug dump payload and return to parking orbit not phased with Orbiter.	ORBITER - Perform phasing orbit maneuver for rendezvous with Tug or return to earth without Tug (effect dependent on time required for return of Tug to parking orbit). TUG - Return to parking orbit and wait for retrieval. PAYLOAD - Placed in sync orbit but not in correct position. GROUND - Possible unscheduled return of some flight elements.
45	XII	Payload	Tug phase and return to parking orbit.	Same as Case 36.

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Table B-1. Gross Abort Effects on STS Elements (continued)

CASE	ABORT REGIME	ELEMENT FAILED	ABORT ACTION	EFFECT ON ELEMENTS
46	XII	Payload	None. Continue mission.	ORBITER - None. TUG - None. PAYLOAD - Failed payload placed in orbit. GROUND - None.
47	XII	Orbiter	Orbiter return to earth.	Same as Case 40.
48	XIII	Tug	Tug phase and return to parking orbit.	SHUTTLE - None. TUG - Determine proper phasing to return to parking orbit for rendezvous and docking with Orbiter. PAYLOAD - Payload scheduled for retrieval remains in orbit. GROUND - Expected payload not returned.
49	XIII	Tug	Tug return to parking orbit not phased with Orbiter.	Same as Case 37 except for payload effect. PAYLOAD - Payload scheduled for retrieval remains in orbit.
50	XIII	Tug	Tug dump retrieved payload and return to parking orbit not phased with Orbiter.	Same as Case 49.
51	XIII	Payload	Tug return to parking orbit without payload.	Same as Case 48.
52	XIII	Orbiter	Orbiter return to earth.	Same as Case 40.

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Table B-1. Gross Abort Effects on STS Elements (continued)

CASE	ABORT REGIME	ELEMENT FAILED	ABORT ACTION	EFFECT ON ELEMENTS
53	XIV	Tug	Tug return to parking orbit not phased with Orbiter.	ORBITER - Perform phasing orbit maneuver for rendezvous with Tug or return to earth without Tug (effect dependent on ΔV capability remaining in Orbiter). TUG - Return to parking orbit and wait for retrieval. PAYLOAD - None. Possible longer stay time in low earth parking orbit. GROUND - Possible unscheduled return of flight elements.
54	XIV	Tug	Tug dump payload and return to parking orbit not phased with Orbiter.	Same as Case 53 except for payload. PAYLOAD - Placed in off-nominal orbit. Possible retrieval by another flight.
55	XIV	Payload	None. Continue mission.	No effects.
56	XIV	Orbiter	Orbiter return to earth.	Same as Case 40.
57	XV	Tug	Tug return to parking orbit not phased with Orbiter.	Same as Case 53.
58	XV	Tug	Tug dump payload and return to parking orbit not phased with Orbiter.	Same as Case 54.
59	XV	Payload	None. Continue mission.	No effects.
60	XV	Orbiter	Orbiter return to earth.	Same as Case 40.

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Table B-1. Gross Abort Effects on STS Elements (concluded)

CASE	ABORT REGIME	ELEMENT FAILED	ABORT ACTION	EFFECT ON ELEMENTS
61	XVI	Tug	Orbiter retrieve Tug/ payload and return to earth.	ORBITER - Must be able to "find" and retrieve a failed Tug. May have to return to earth empty if remaining ΔV is not sufficient to "find" the Tug. TUG - Must be able to safe itself and remain stable for Orbiter docking. May have to remain in low earth orbit for another Orbiter flight. PAYLOAD - May have to remain in low earth orbit for another Orbiter flight. GROUND - Unscheduled return of flight elements.
62	XVI	Payload	None. Continue mission.	No effects.
63	XVI	Orbiter	Orbiter return to earth empty.	ORBITER - None. TUG - Remain in low earth orbit for retrieval. PAYLOAD - Remain in low earth orbit for retrieval. GROUND - Late return of some flight elements.

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